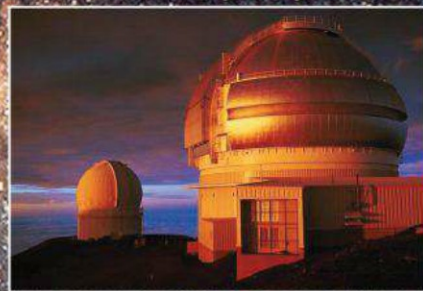


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50 GIANT TELESCOPES EXPLORED

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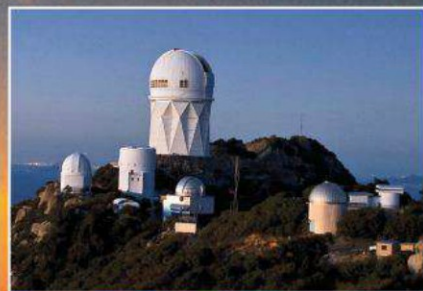
Peer into space from . . .



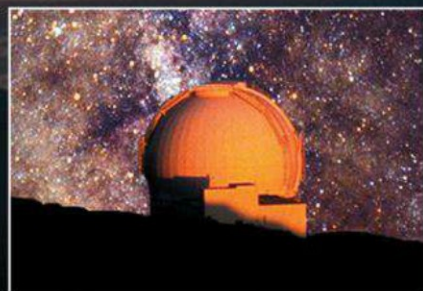
The summit of Mauna Kea, Hawaii



The world's driest desert in Chile



Historic sites in Arizona and California



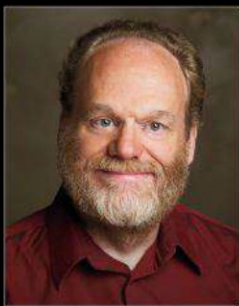
The majestic Canary Islands

PLUS!

Orbiting scopes of today and tomorrow

50 biggest telescopes on Earth mapped

HISTORY SPECIAL: How the telescope remade the universe



If Galileo could see us now

Sometime during the first decade of the 17th century, Dutch spectacle makers figured out how to make distant objects appear closer by arranging two lenses just so. At the time, most people didn't think of the new instrument as anything more than an entertaining diversion.

But when Italian scientist Galileo Galilei (1564–1642) got wind of the invention, he immediately saw its potential. He quickly built a better version and in 1609 turned it toward the sky. He saw stars in the band of the Milky Way, mountains on the Moon, satellites orbiting Jupiter, and Venus going through phases. Galileo's observations transformed astronomy, science, and society in general.

In the three centuries following Galileo's findings, astronomers continued to build bigger and better telescopes. Yet these sophisticated instruments typically remained close to the people and institutions that paid for them. In the days before light pollution destroyed the night skies near population centers, no one thought twice about placing telescopes in the heart of a city or on a college campus. And in an age when transportation was neither easy nor cheap, convenience usually won arguments about where to erect observatories.

In the 20th century, however, the science of telescope making exploded. Scientists could cast, grind, and polish large mirrors with exquisite precision. The people who paid for these giant scopes wanted them used as often as possible and under the best conditions. Isolation became necessary to avoid the lights of civilization. Clear weather maximized the number of

observing hours during the year. And a steady atmosphere overhead guaranteed the crisp images that these new telescopes could deliver.

Today, a map of the world's great observatories skews heavily toward such sites. More than 80 percent of the world's largest telescopes now reside on mountaintops in either the southwestern United States, Hawaii, Chile, or the Canary Islands.

Fortunately, travel today is much more convenient and less expensive than what our ancestors faced 100 years ago. An astronomy enthusiast can make a pilgrimage to many of these sites. Seven days focused on the great observatories of the American Southwest will get you to nearly one-quarter of the world's largest scopes — and a plethora of other important instruments.

A solid week will get you to an equal number of giant scopes in the high desert of Chile. And you can see almost as many of these modern marvels in a single day at Hawaii's Mauna Kea or the Canary Islands' Caldera de Taburiente (although I'd recommend spending a bit more time in these scenic locales).

Scientists have come a long way since Galileo first pointed his 1-inch telescope toward the heavens. He would be amazed at the tools astronomers now use routinely to explore the cosmos. And you will be, too, if you take the time to visit these wondrous places, either in person or through the pages of this publication.

Richard Talcott

Richard Talcott
Editor

THE WORLD'S GREATEST TELESCOPES

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Unhindered by Earth's distorting atmosphere, space telescopes bring us our clearest view of the cosmos yet.

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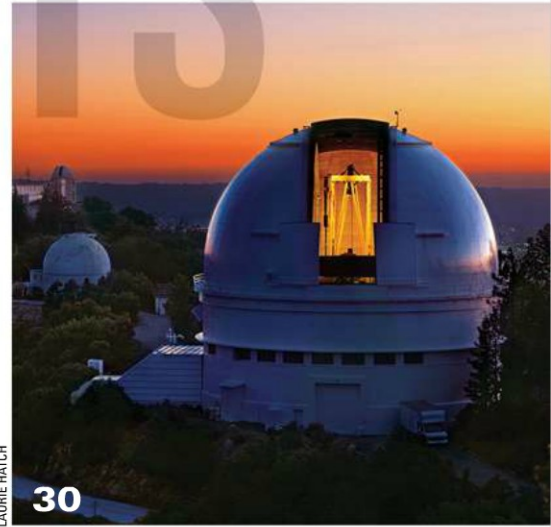
Arrays of antennas and dishes up to 1,000 feet across make radio telescopes the biggest observatories on Earth.

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LAURIE HATCH



DANIEL LÓPEZ AND THE IAC'S PHOTO ARCHIVE



NASA

Within half a century of its invention in 1608, the telescope had transformed our view of the cosmos and Earth's place in it.

by Raymond Shubinski

How the TELESCOPE remade the universe

No one questions that the invention of the telescope transformed science. Yet far fewer people realize this 1608 invention also revolutionized philosophy, culture, and religion. In the first half of the 17th century, this new optical instrument went from a toy to an agent of spectacular change.

At first, seeing and believing did not go hand in hand. Some wondered whether this newfangled combination of lenses could trick the senses into perceiving falsehoods. It took the dedication of many individuals to prove the telescope's value and move Earth to its rightful place in the cosmos.

Historians have long debated the origin of the telescope. Many scholars credit spectacle maker Hans Lipperhey of Middelburg, Netherlands, with inventing it. In late September 1608, Lipperhey presented the instrument to Prince Maurice, then head of state of the Dutch Republic. Lipperhey was looking to get a patent. Within days, two other individuals

appeared in The Hague with similar instruments and similar requests.

In 1642, Pirre Borel published a book titled *The True Invention of the Telescope*. His account favors Dutchman Zacharias Janssen. More recently, the trail has led to a Spanish optician. Like the blurry images delivered by early telescopes, the true inventor likely will remain obscure.

The device that emerged was simple. It required just two lenses to produce a magnified image of a distant object. A weak convex lens, called the objective, sat at the

Historians have long debated the origin of the telescope.

front of the telescope tube and a strong concave lens, the eyepiece, at the rear. The story that Lipperhey accidentally discovered the telescope while inspecting two eyeglass lenses appears to be incorrect. These telescope lenses were not used for eyeglasses. In fact, if you hold a weak convex and strong concave lens close together, a distant object will appear smaller.

The invention takes off

Whatever the true story of its invention, the new device spread like wildfire across

Europe. At first, it seemed useful only as a parlor toy or possibly as a military aid. Spanish artist Diego Velázquez captured the telescope's military importance early on. In 1625, Spanish forces conquered the Dutch city of Breda. A 1634 Velázquez painting shows Spanish General Ambrogio Spinola holding a telescope as he accepts the sword of surrender. Yet the telescope as an agent of philosophical, religious, and scientific change was under way well before these military events.

Just eight months after Lipperhey's presentation to Prince Maurice, an Italian professor of mathematics received news of the device and produced his own, better version. Galileo Galilei lived in Padua with his common-law wife and children. Like teachers in all eras, Galileo always looked for ways to make extra cash. At first, he sold his instrument "for far seeing" to merchants, who used the device to keep tabs on ships coming into port. Being a man of ambition and imagination, however, Galileo soon turned his telescope skyward. What he saw changed the course of the modern world.

The late 16th and early 17th centuries were turbulent times. Martin Luther had ignited the Protestant Reformation in 1517 when he nailed his 95 Theses to the doors of the Castle Church in Wittenberg,

Contributing Editor **Raymond Shubinski** is a museum and planetarium consultant who loves the history of astronomy.

GALILEO GALILEO

GALILEO TURNED HIS TELESCOPE TO THE SKY for the first time in 1609. His observations launched a 50-year era of discovery that transformed our ideas about the universe.

GALILEO GALILEI



SIDEREVS NVNCIVS

MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò

PHILOSOPHIS, atq; ASTRONOMIS, qua à
GALILEO GALILEO
PATRITIO FLORENTINO

Patavini Gymnasij Publico Mathematico

PERSPICILLI

Novæ & præsertim beneficio sunt observata in LVNÆ, & FIXIS STELLIS, LACTEO CIRCULO, STELLIS NEBULOSIS,

Apprime verò in
QVATVOR PLANETIS
Saturno, Iovis, Martis, & Veneris, quos, nemini in hunc usque
seculum, nomen Author deprædicavit, præsertim, aique

MEDICEA SIDERA

NUMEROSISSIMIS DECREVIT.

Tab. VII.

Ori. * ○ * Occ.

min. 10. hæc erat aliquanto minor orientali. Sed hora 6. orientalis proximior erat Iovi distabat nempe mi. 6. sec. 50. occidentalis verò remotior fuit, scilicet min. 12. Fuerunt in vtraque observatione in eadem recta, & ambæ satis exiguæ, præsertim orientalis in secunda obseruatione.

Die 18. Ho. 1. tres aderant Stellæ, quarum duæ occidentales, orientalis verò vna: distabat orientalis à Iove

Occ.

GALILEO GALILEI

GALILEO GALILEI

GALILEO GALILEI



THE SIEGE OF BRED A ended in 1625 when Spanish forces defeated those of the Dutch city. In this 1634 painting by Diego Velázquez, notice the telescope clutched by the victorious General Ambrogio Spinola.

Germany. Not long after, the Catholic Church began the Counter-Reformation, which made it risky to challenge Church dogma. In 1600, an Inquisition tribunal ordered Giordano Bruno burned at the stake for holding various heretical views, including that of a Sun-centered (heliocentric) universe. Despite this dangerous climate, Galileo knew he was on to something big with his telescope and that he wasn't the only one stargazing with this new instrument.

In March 1610, Galileo rushed to publish his book *Sidereus Nuncius*, or *Sidereal Messenger*. In this small volume, Galileo challenged the accepted knowledge and wisdom of the past 2,000 years. With his improved telescope of about 30 power, he saw the Moon as a rough world full of mountains, valleys, and smooth "seas."

Farther away, fuzzy objects melted into clusters of myriad stars, and the Milky Way resolved into millions of stars too faint to be seen with the unaided eye. Most amazing of all, the planet Jupiter

had its own retinue of four satellites, which Galileo named the Medicean stars.

Galileo dedicated *Sidereal Messenger* to Cosimo II de' Medici in the hope of landing a job in Florence with the Grand Duke as his patron. The ploy worked, and the Grand Duke appointed Galileo his chief mathematician and philosopher. Galileo also became chief mathematician at the University of Pisa. With no teach-

Galileo always looked for ways to make extra cash.

ing duties, he was free to devote himself entirely to research.

Four moons stun the world

Jupiter's four moons intrigued Galileo, and he soon compared them to a solar system in miniature. He used these observations to strengthen his argument for a Sun-centered universe, introduced during the previous century by Polish cleric Nicolas Copernicus. Galileo's lunar

Telescope timeline

- 1608** Hans Lipperhey tries to patent the newly invented telescope.
- 1610** Galileo Galilei discovers four jovian moons and the phases of Venus.
- 1655** Christiaan Huygens discovers Saturn's largest moon, Titan.
- 1666** Giovanni Cassini discovers one of Mars' two polar caps.
- 1675** Ole Rømer studies Jupiter's moons to deduce the speed of light.

observations had already unseated the idea that all celestial bodies were perfect. Not only had he seen the uneven topography of the Moon's surface, but he also had measured the height of lunar mountains from the shadows they cast. Still, Galileo had to fight for change on two fronts.

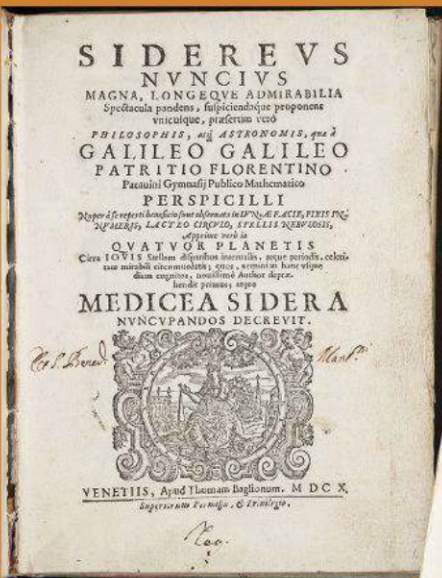
In the 4th century B.C., the great Greek philosopher Aristotle refined the concept of an Earth-centered (geocentric) universe along with the basics of physics. Some 500 years later, Greek astronomer Claudius Ptolemy formalized the model. Although Aristotle was a pagan, the Catholic Church had come to view his ideas about the physical world as gospel truth. This authority was ingrained in almost all educated people.

Could a simple instrument using two pieces of glass unseat 2,000 years of learning and truth? Many scholars thought the distortions inherent in these early telescopes gave views that couldn't be trusted. On a number of occasions, Galileo pointed a telescope at distant buildings during daylight to convince his audience that the nighttime views were trustworthy as well. This strategy didn't work with everyone. After all, Aristotle asserted that all things beyond Earth's realm were perfect.

Galileo was not the only person studying the heavens with a telescope. German Jesuit Christoph Scheiner, who was already well-known for inventing the pantograph (a device used to duplicate drawings at an adjustable scale), began to observe the Sun in 1611. Like Galileo, Scheiner discovered that this heavenly object was far from perfect.

Scheiner projected the Sun's telescopic image onto a white board and found the solar disk marked with dark spots. Was his telescope deceiving him? Scheiner was convinced of the spots' reality, and he published his observations in January

Galileo's first views

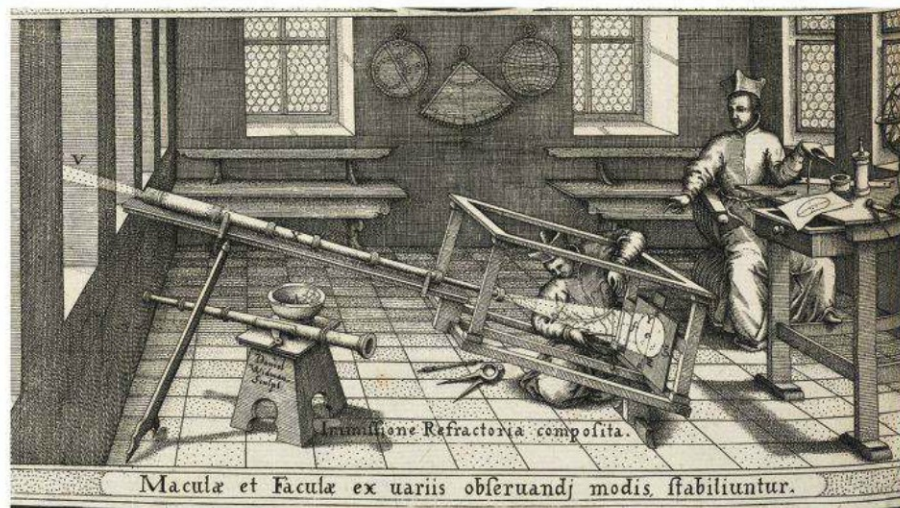


▲ **SIDEREUS NUNCIVS**, or *Sidereal Messenger*, laid out Galileo's initial observations. In it, he related his discoveries of myriad stars in the Milky Way, an imperfect Moon, and four satellites orbiting Jupiter.

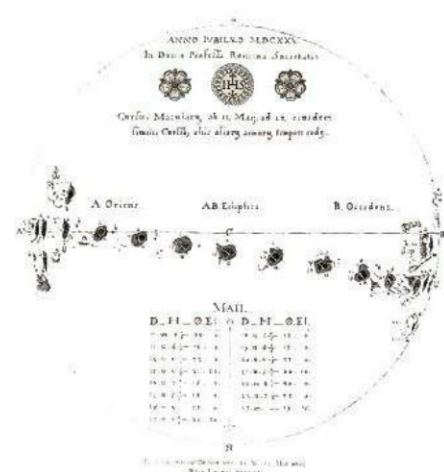
► **GALILEO'S FIRST QUARTER MOON** shows large craters, tall mountains, and smooth, dark "seas," all signs that imperfection exists beyond Earth's realm.



► **JUPITER'S MOONS APPEAR AS ASTERISKS** in Galileo's initial drawings. The Italian scientist discovered Io, Europa, and Callisto January 7, 1610, and Ganymede six days later.



CHRISTOPH SCHEINER AND AN ASSISTANT observed and recorded sunspots by projecting the Sun's image through a telescope onto a white card.



SCHEINER'S DETAILED OBSERVATIONS recorded dark "blemishes," another sign that all was not perfect beyond Earth.

1612. When Galileo heard about Scheiner's discovery, he was furious and began a rancorous debate over who should get credit. Whoever saw them first, the sunspots' mere existence pounded another nail into Aristotle's perfect cosmos.

Going through a phase

The most-damaging blow to Aristotle's universe came with Galileo's observations of Venus. Venus never strays far from the Sun in our sky, a fact the geocentric model

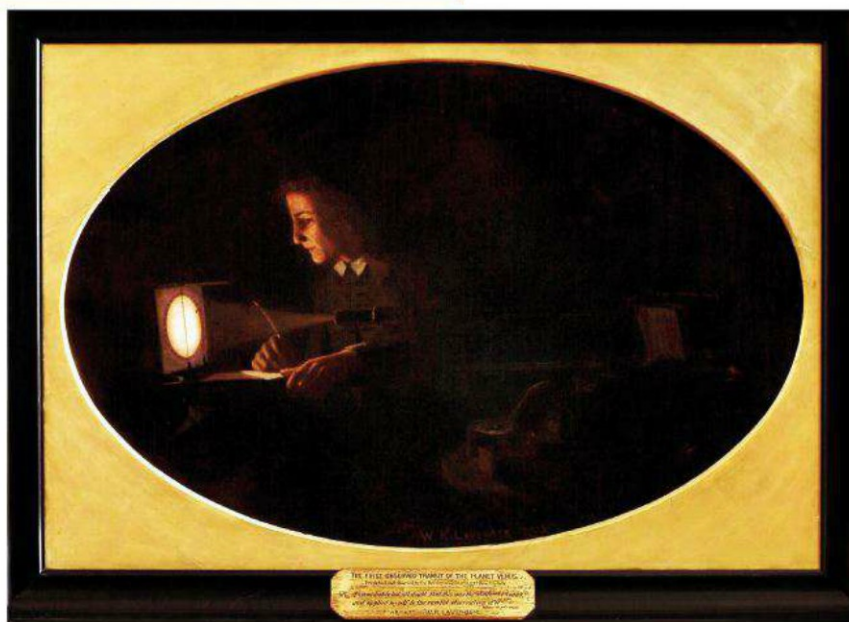
explains by requiring Venus to circle a point that remains on a line between the Sun and Earth. In this arrangement, Venus always would show a crescent phase.

When Galileo turned his telescope on Venus, he saw it go through all phases just like the Moon. The only explanation: Venus orbits the Sun and not Earth.

Galileo's observations, publications, and obstinacy finally brought him into full conflict with Pope Urban VIII. He ultimately denied what he knew to be

truth and stopped his astronomical investigations. Galileo eventually lost his eyesight and died under house arrest.

Although Galileo made the most significant observations of Venus, he wasn't the only person who studied our sister planet. At the same time Galileo was scanning the heavens with his telescope, German astronomer Johannes Kepler was working through the mathematics that led to his three laws of planetary motion. Kepler based these laws on the



J.W. LAVENDER PAINTING, COURTESY VASTLEY HALL MUSEUM AND ART GALLERY

JEREMIAH HORROCKS OBSERVED VENUS during its 1639 transit of the Sun. He and his friend William Crabtree were the only persons known to see this transit.

heliocentric model of the universe, and they allowed him to make detailed predictions of the planets' motions. His calculations showed that Venus would cross in front of the Sun in 1631. Unfortunately, this transit occurred when the Sun was below the horizon throughout Europe.

A second opportunity came eight years later. The young English cleric Jeremiah Horrocks calculated that Venus would transit the Sun late Sunday, November 24, 1639. Horrocks had to attend to his church until 3 P.M., but then made a dash for his telescope. Although the day had been cloudy, the sky cleared by 3:15 P.M., and Horrocks could see Venus' small dark disk as it progressed across the Sun's face. William Crabtree, a friend of Horrocks'

who lived 30 miles away, also viewed the transit. Both men used Galilean telescopes to project the Sun's image onto a white card. This simple method provided profound evidence for Kepler's laws and for the Copernican heliocentric universe.

By the time Galileo died in 1642, the telescope had become an indispensable tool for nearly every astronomer. Yet the simple optics of those early refractors limited their usefulness. Poor optics even fooled Galileo. At one point, he sent out a secret communication declaring Saturn

was a triple planet. In reality, he was seeing a blurred image of the planet's rings.

Building the scope's power

Early telescopes had two primary limitations: They suffered from spherical and chromatic aberrations. These problems compounded the difficulty of getting clear views of planets and stars. To make matters worse, greater magnifications exacerbate the effects.

Spherical aberration causes fuzzy or blurred images. Lenses made with spherical surfaces (by far the easiest to

The challenge in building a telescope of these dimensions was as big as the scope itself.

manufacture and the only shape early lens makers could produce) can't bring all light rays to the same focus. Rays that pass through the lens near its edge focus closer than rays that pass nearer the center.

Chromatic aberration produces color fringes around images. When light passes through a lens, the different colors that make up white light bend by different amounts. Blue bends the most and red the least. Focusing on the green image results in the out-of-focus red and blue images combining to form a purple fringe.

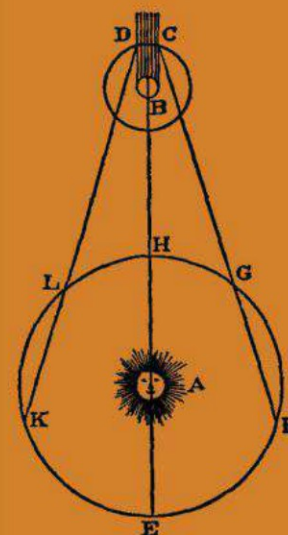


FIG. 70.

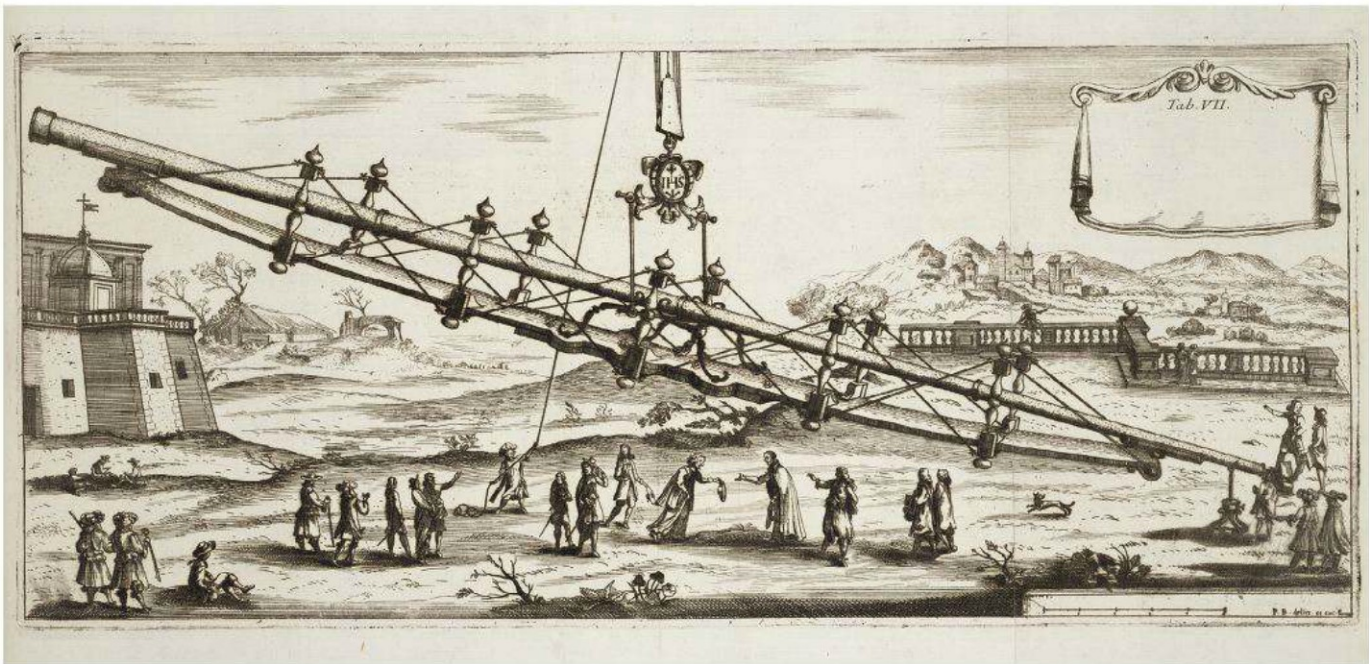
OLE RØMER MEASURED LIGHT'S SPEED by observing eclipses of Jupiter's moons. When Earth and Jupiter approached each other, the times between eclipses were shorter than when the two planets were moving apart.

The best 17th-century remedy for both aberrations was to shape the objective lens so it had a much longer focal length (in other words, light focused farther from the lens). That is why early telescope makers made their instruments incredibly long.

In the early 1640s, successful brewer Johannes Hevelius turned his energy to astronomy. From his rooftop observatory in Danzig (now Gdansk, Poland), Hevelius began observing the Moon with refracting telescopes about 12 feet long. He recorded hundreds of lunar features and published a famous lunar atlas, *Selenographia*, in 1647.

In the mid-1650s, Hevelius heard about the observations of Dutch brothers Constantine and Christiaan Huygens, who used exceedingly long telescopes. The brothers had established Saturn not as a triple planet, but a world surrounded by "a ring, thin, plane, nowhere attached, and inclined to the ecliptic." Word of this success set Hevelius to making telescopes up to 150 feet long with objective lenses not more than 2 inches in diameter.

The challenge in building a telescope of these dimensions was as big as the scope itself. Hevelius erected a tall mast from which he suspended sectional tubes that held the objective lens high in the air and positioned the eyepiece near the observer on the ground. A crew of sailors handled the ropes and rigging to maneuver the ungainly giant. On a visit to



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FRANCESCO BIANCHINI VIEWED VENUS through this monster telescope, which was based on a design by Giuseppe Campani. Bianchini observed Venus' phases and saw vague, dark markings that he erroneously thought represented surface features.

Danzig, Edmond Halley proclaimed the telescope "useless." Indeed, it could be used only under the best conditions.

Christiaan Huygens developed a more usable "aerial telescope," also about 150 feet in length. Huygens mounted the objective lens in a short iron tube, which he attached to a ball-and-socket joint and counterbalanced with a lead weight. He then placed this entire assembly on a tall mast. Huygens operated the objective lens by a long cord attached to the eyepiece, which he mounted on a short ladder (see the drawing at right).

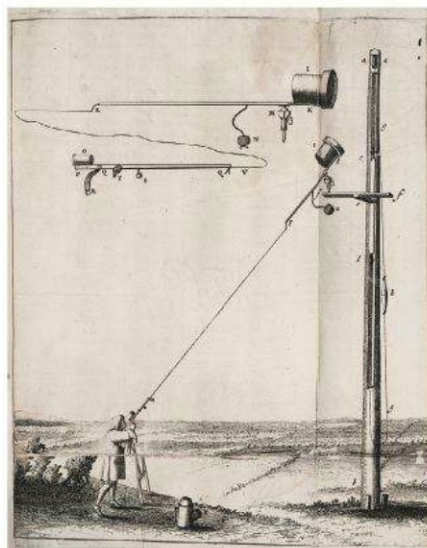
Huygens also improved the eyepiece by using a compound design of two thin convex lenses. Observers still use a modified version of the Huygens eyepiece. A remedy to these high-flying telescopes came from Edmond Halley's good friend, Isaac Newton. Newton built the first reflecting telescope, which uses a mirror instead of a lens to focus light, eliminating chromatic aberration.

Tripping the light fantastic

But the refracting telescope still held surprises for astronomers, including the first measurement of the speed of light. That revelation arose from the needs of the mercantile and war ships that plied 17th-century waters. The seafarers' most pressing problem was knowing their position at sea. They could find latitude easily by observing the Sun or stars. Longitude

proved tricky. To pinpoint longitude, sailors had to know the difference in time between their position and that of a fixed location, such as the Royal Greenwich Observatory near London, England.

Galileo had thought to use the timing of Jupiter's moons as they orbit the planet as a kind of celestial clock. Although the idea was solid, the rolling, pitching deck of a ship at sea made such detailed observations impossible.



CHRISTIAAN HUYGENS BUILT this mammoth aerial telescope that measured nearly 150 feet from lens to eyepiece. LINDA HALL LIBRARY OF SCIENCE, ENGINEERING & TECHNOLOGY

In 1671, Danish astronomer Ole Rømer and his French colleague, Jean Picard, observed about 140 eclipses of Io, Jupiter's closest large moon. They viewed these eclipses from the island of Hven, Tycho's old stomping grounds near Copenhagen. Meanwhile, Italian-French astronomer Giovanni Cassini made the same observations from Paris. By comparing the time lag in the eclipse observations, the astronomers were able to determine the difference in longitude between Hven and Paris.

Rømer didn't stop there, however. He continued to time Jupiter's moons. He soon noticed a shift from the predicted eclipse times. He realized that as Earth approached Jupiter, the time between eclipses shortened. As Earth pulled away from Jupiter, the time increased.

Rømer deduced that light must have a finite speed. He calculated that light travels at roughly 125,000 miles per second. Although Rømer's value was too small by a factor of one-third, the idea was sound. Not all scientists fully accepted this astounding discovery. It would take another 50 years, until 1727, before English astronomer James Bradley confirmed light's finite speed.

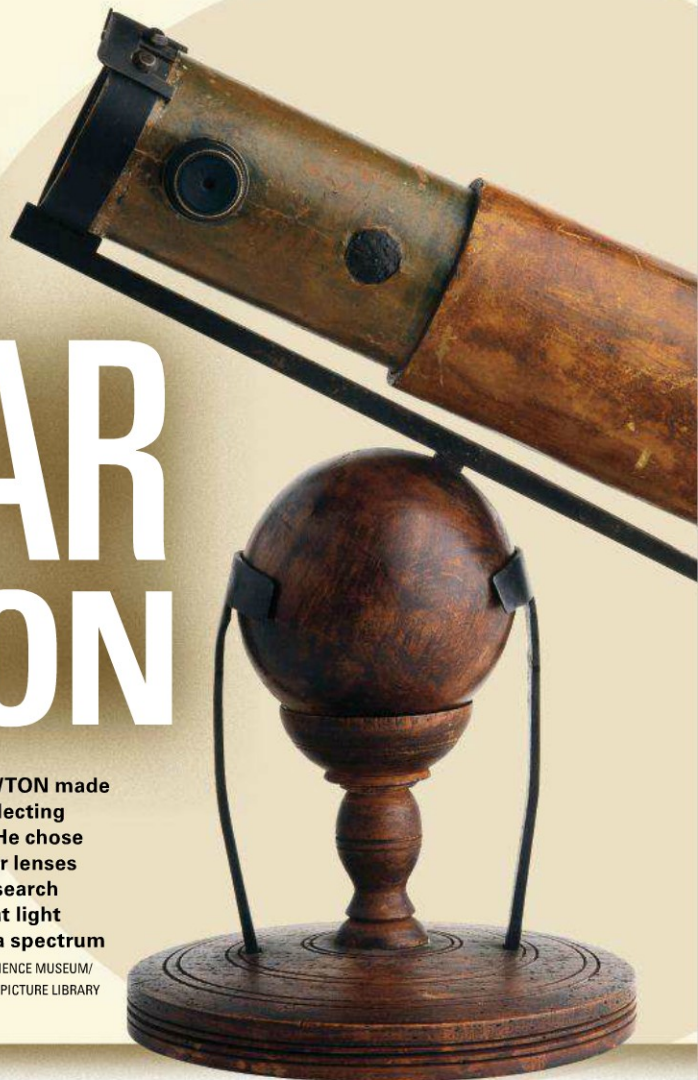
Within half a century of its invention, the telescope had allowed astronomers to remake the universe. The cosmic changes launched by this instrument continue to reverberate 400 years later. ■

The telescope's 400-YEAR REVOLUTION

Early telescopes were about 1 inch wide; today's span some 33 feet. Here's how this crucial tool moved forward.

by Liz Kruesi

ISAAC NEWTON made the first reflecting telescope. He chose mirrors over lenses after his research showed that light comprises a spectrum of colors. SCIENCE MUSEUM/SCIENCE & SOCIETY PICTURE LIBRARY



When Galileo Galilei pointed his looking glass to the sky in 1609, he viewed a world never before seen. Even though his refractor had a tiny field of view and distorted optics, he was the first human to observe the Moon as an imperfect sphere. This new capability to observe proved the era's scientific beliefs were inaccurate.

Since 1609, observers have opened a new door to the universe with their modified looking glasses. The telescope's transformation has encapsulated more than 400 years of trial and error and awe.

Rise of the reflector

The first telescopes — refractors — used lenses to collect and focus light. However, a lens focuses different colors of light to different points. This effect — called chromatic aberration — caused color fringes around objects viewed with early refractors. To resolve this problem, early observers moved away from refractors and toward telescopes made of mirrors.

Isaac Newton determined an achromatic telescope lens was impossible.

In 1668, he instead made a reflecting telescope using speculum metal — an alloy of copper and tin. He used a spherical primary mirror and a flat secondary mirror angled 45° to reflect the light to one side of the tube (and also to the attached eyepiece). This scope's aperture was 1½ inches and magnified objects 40 times.

Although Newton built the first reflector, he wasn't the one who came up with the concept. In 1663, James Gregory designed a two-mirror combination. His concept features a concave parabolic primary mirror and a concave ellipsoid secondary mirror. Unfortunately, in the 1660s no one could grind a mirror surface other than spherical, and therefore the Gregorian design was useless.

The third reflecting telescope concept came in 1672 from Frenchman Laurent Cassegrain. In the Cassegrain design, while the primary is a parabola like the Gregorian, the secondary mirror is a convex hyperboloid instead of a concave ellipsoid. But like the Gregorian, the time's technology meant the Cassegrain design couldn't move past the proposal stage.

These early reflecting telescopes also suffered from a type of aberration, called spherical aberration. When a telescope uses a spherical mirror, light rays near the mirror's center reflect to a different focal point than light rays near its outer edges. Until opticians could grind mirrors into other shapes, spherical aberration would remain a problem and mirrors would take a back seat to refractors.

Return of the refractors

Refracting telescopes also had problems besides their chromatic aberration. Their glass had imperfections, and they had extremely long tubes to accommodate the primary lens' focal length. In 1729, the first of these problems experienced drastic improvement with Chester Moor Hall's development of the achromatic lens. Hall's design combined two pieces of glass — each with a different index of refraction, or how much the glass bends light. Using concave flint glass and convex crown glass, Hall created a lens that brought most wavelengths to the same focus.

Reflecting telescopes
spent **40 years** at
a standstill until opticians
figured out how to grind
non-spherical
mirrors.

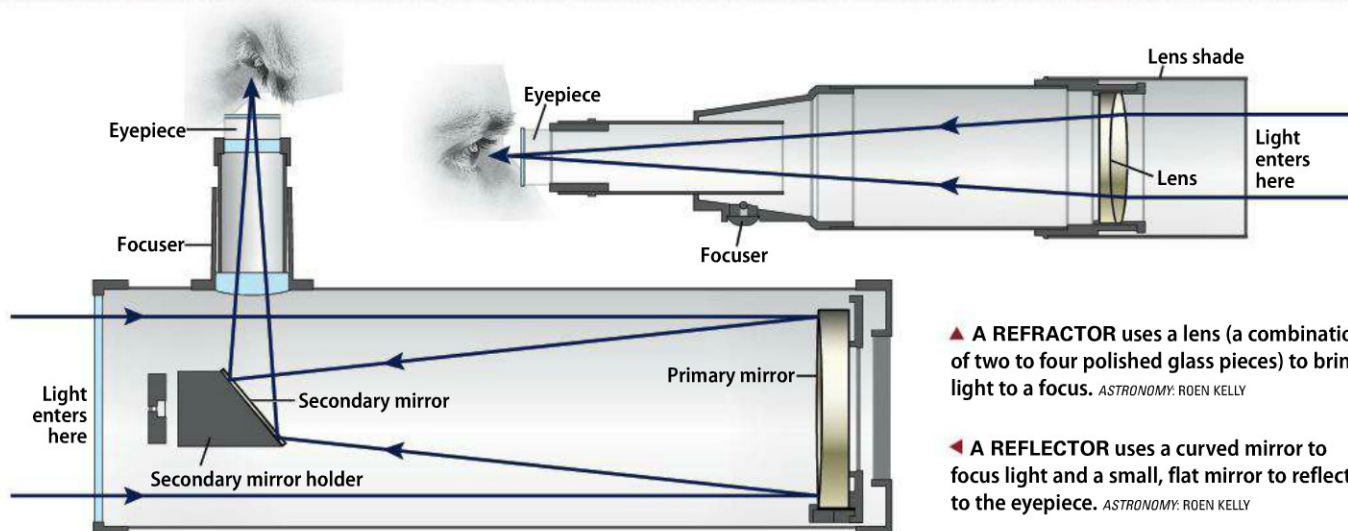


JOHN HADLEY'S GREGORIAN reflecting telescope was one of the first telescopes to use a parabolic mirror. This telescope, from 1724, was made just a few years after Hadley's first Gregorian.

SCIENCE MUSEUM/SCIENCE & SOCIETY PICTURE LIBRARY



THE 9.5-INCH DORPAT REFRACTOR was the first telescope to use an equatorial mount. Joseph Fraunhofer learned in the early 1800s how to make large lenses free of imperfections. He made this excellent refractor in 1824. ANDRES KUPERJANOV, TARTU OLD OBSERVATORY



▲ **A REFRACTOR** uses a lens (a combination of two to four polished glass pieces) to bring light to a focus. ASTRONOMY: ROEN KELLY

◄ **A REFLECTOR** uses a curved mirror to focus light and a small, flat mirror to reflect it to the eyepiece. ASTRONOMY: ROEN KELLY

In 1765, Peter Dollond found a way to eliminate chromatic aberration altogether. Dollond fit three different lenses together to create the triplet objective. Unfortunately, even with this major improvement, refractors still had a problem: Lenses larger than about 4 inches contained imperfections, such as bubbles and streaks, that altered the appearance of

celestial objects. These setbacks halted the evolution of refractors until someone could make a larger lens free of defects.

Enter Pierre Louis Guinand, a Swiss craftsman. In 1785, after almost 20 years of trial and error, Guinand invented a new technique that used a porous clay stirrer instead of a wood rod to blend the molten glass. With this fireclay stirrer, bubbles

rose to the surface and the glass stayed mixed longer. Guinand's lenses, as a result, were nearly free of defects.

Through collaboration with a German financing firm, Guinand taught his lens-making methods to physicist Joseph Fraunhofer, who built a number of excellent telescopes. In fact, the 9.5-inch diameter Dorpat refractor he built

After refractors moved past the 4-inch size barrier, it was only a matter of time before large refractors were everywhere.

◀ **THE 40-FOOT TELESCOPE**, with a primary mirror of 48 usable inches, was William Herschel's largest scope, but it wasn't his favorite. Instead, he preferred his "large 20-foot" that had an 18.5-inch-diameter mirror. The 40-foot was difficult to maneuver and took too long to adjust to the ambient temperature. This telescope remained the largest in the world from 1789 until 1845.

COURTESY ADLER PLANETARIUM & ASTRONOMY MUSEUM, CHICAGO, ILLINOIS

▶ **WILLIAM HERSCHEL** used a telescope similar to this one to discover Uranus in 1781. This Newtonian reflecting telescope is 7 feet long to house the focal length of a roughly 6-inch-diameter mirror. In this image, the telescope tube is original while the mount is a modern reproduction of Herschel's design. COURTESY ADLER PLANETARIUM & ASTRONOMY MUSEUM, CHICAGO, ILLINOIS

in 1824 was the first scope to use an equatorial mount.

Reflectors play catch-up

Reflecting telescopes spent 40 years at a standstill until opticians figured out how to grind non-spherical mirrors. In 1721, John Hadley taught himself how to grind speculum metal, and he and his two brothers ground a parabolic mirror for a Gregorian telescope.

Few advanced telescope making more than German-born English astronomer William Herschel. In 1773, he began

producing small telescopes (a few inches in diameter). Then in 1778, he polished a speculum mirror about 6 inches in diameter. This telescope, 7 feet long and of Newtonian design, was the instrument he used to discover the planet Uranus some 2½ years later.

Herschel's reflecting surfaces, like other speculum mirrors, required constant polishing. For most of his telescopes, he'd create two mirrors so that he could continue observing while polishing the other. In 1783, Herschel built his most-used telescope; it had a roughly 18.5-inch-diameter mirror and a 20-foot-long tube. His next scope was a 49.5-inch aperture instrument (it had 48 "usable" inches).

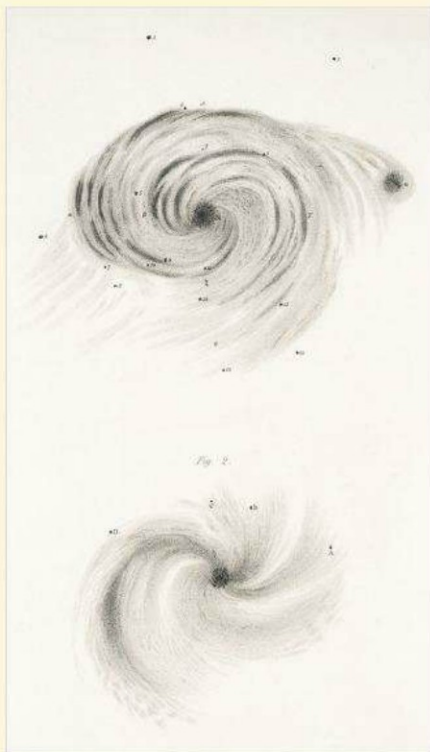
Herschel housed this mirror in a 40-foot-long tube. He raised and lowered his 20-foot and 40-foot telescope tubes using cables supported by wood frames. The 40-footer was the largest telescope from 1789 until William Parsons, the third Earl of Rosse, completed his 72-inch version in 1845.

Parsons wanted a bigger and better telescope than Herschel, and the only way he could get one was to build his own. Lucky for him, he also had unlimited resources (both money and materials). So he set to work at Birr Castle, Ireland.

Parsons first cast a 15-inch, then a 24-inch, and finally a 36-inch mirror to perfect his method. His 36-inch one produced brighter and sharper images than Herschel's mirrors. So what was Parsons' next project? Build it bigger — he doubled the diameter.

After his 72-inch mirror was cast, it took more than 16 weeks to cool. During the polishing process, the mirror broke.

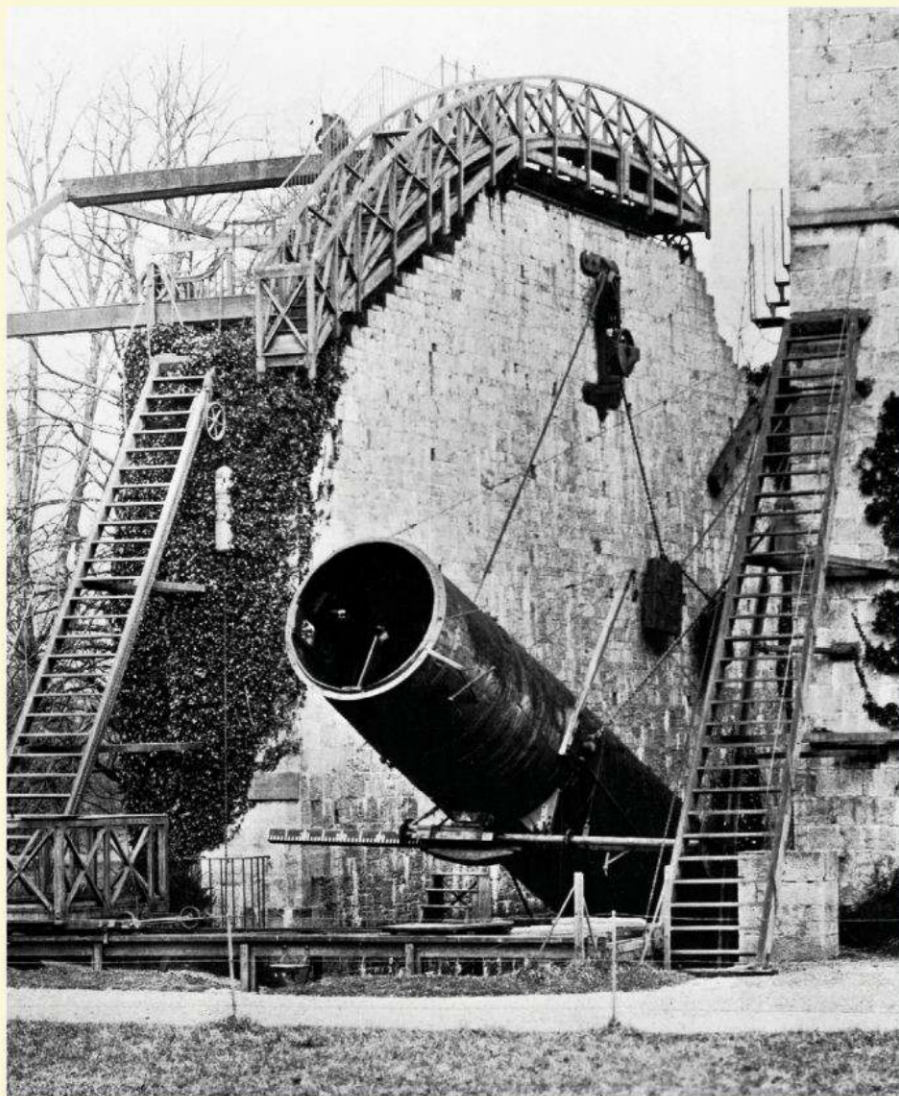
Liz Kruesi is an associate editor of *Astronomy*.



▲ **THE SPIRAL STRUCTURE** of the Whirlpool Galaxy (M51), and other so-called nebulae, showed itself through the 72-inch “Leviathan of Parsonstown” during William Parsons’ observations.

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► **THE LEVIATHAN OF PARSONSTOWN** was the largest telescope built from 1845 until the 100-inch Hooker surpassed it in 1917. The Leviathan, created at Birr Castle, Ireland, fell into disrepair in 1908 and was dismantled in 1914.



SCIENCE MUSEUM/SCIENCE & SOCIETY PICTURE LIBRARY

Undeterred, Parsons cast a second, third, fourth, and finally a fifth mirror. This huge mirror weighed 4 tons — too much for wood beams to support it. So Parsons built stone walls to hold the 56-foot-long tube. Parsons and his assistants completed this “Leviathan of Parsonstown” in 1845.

Because of the mounting system, the scope could move only up and down and slightly side to side, which limited its view. The weather also never seemed to cooperate. With this scope, Parsons observed the spiral structure of the Whirlpool Galaxy (M51) and other “nebulae,” but because of limited observing time, the “Leviathan” proved less than useful in many ways. It remained, however, the world’s largest telescope ever built until 1917.

The last large telescope sporting a speculum mirror was completed in 1868. Six years earlier, a committee of astronomers and telescope makers discussed

building a Southern Hemisphere telescope. The committee chose a 48-inch-diameter reflector for Melbourne, Australia. And even though silvered glass had recently made an appearance, they chose a speculum mirror because they felt silver on glass would tarnish too quickly and possibly damage or break as a result of the weather. They used the Melbourne Telescope for about 10 years before the scope fell into disrepair.

And so the era of metal mirrors ended. The advancement of large reflectors again stalled for decades. Because speculum mirrors tarnished easily and coated mirrors were still in their infancy, observers typically chose glass refractors over reflectors.

Giant refractors emerge

After refractors moved past the 4-inch size barrier, it was only a matter of time

before large refractors were everywhere. With interest in astronomy growing, Boston, Massachusetts, citizens pooled their resources for a 15-inch refractor for Harvard College Observatory in Cambridge. This telescope, completed in 1847, was the largest in the United States for 20 years until finally surpassed by one from a top-notch American optics firm.

Upon peering through the Harvard refractor, Alvan Clark felt he could create a superior lens. Clark was a portrait painter who occasionally dabbled in mirror- and lens-making, but he wasn’t trained as an optician or astronomer. After learning the trade, he would build some of the finest refractors in the world.

The Alvan Clark & Sons partnership started producing small lenses in 1844. By the end of the century, Clark refracting telescopes were in almost every large U.S. observatory and scattered across the



THE 36-INCH LICK REFRACTOR saw first light in 1888. One of the two lens blanks broke during transport, and it took 18 attempts to make a replacement blank. This Clark telescope is still used today for infrequent research and public viewing atop Mount Hamilton in Northern California. LICK OBSERVATORY



THE LARGEST WORKING REFRACTOR ever built, the Yerkes 40-inch, saw first light in 1897. Charles Tyson Yerkes gave the money — some \$300,000 — needed to fund the 40-inch telescope, mount, and observatory.

SPECIAL COLLECTIONS RESEARCH CENTER, UNIVERSITY OF CHICAGO LIBRARY

globe. Clark made the world's largest refractor five different times.

In 1862, Clark completed an 18½-inch equatorial for the Old University of Chicago. This telescope is still used today at the Dearborn Observatory at Northwestern University, north of Chicago.

In 1870, the U.S. Naval Observatory asked its astronomer, Simon Newcomb, to find the best and biggest telescope \$50,000 could buy. He contracted Clark, who created a doublet lens — one piece flint and the other crown — that was 26 inches in diameter and weighed 110 pounds. In 1873, the Naval Observatory telescope saw first light, and it remained the largest refractor in the world for 12 years.

Many large refractors were built in the 1870s through 1890s. In 1885, a telescope with a 30-inch Clark lens saw first light at Pulkovo Observatory near Saint Petersburg, Russia. In 1885, Clark began

work on the Lick Observatory 36-inch refracting telescope, which would sit atop Mount Hamilton in Northern California. The site, roughly 4,200 feet above sea level, provided optimal observing conditions. Once complete, the Lick 36-inch remained the largest refractor from 1888 until 1897.

A few years later, the University of Southern California commissioned a 40-inch objective lens from Clark. However, the funds fell through, and Clark had two glass disks for a 40-inch objective lens but no buyers. Enter George Ellery Hale of the University of Chicago.

Recognizing the importance of an observatory for astrophysics academia, Hale and the university's president convinced Charles Tyson Yerkes, a Chicago railway magnate, to fund the telescope lens, mount, and the rest of the observatory. Hale chose a site in southern Wisconsin,

on the shore of Lake Geneva. The cold winter nights provided clear seeing.

The Yerkes 40-inch saw first light in 1897. This giant telescope's tube is 64 feet long and weighs 6 tons (not including the mounting system). The lenses themselves weigh some 500 pounds. The Yerkes refractor, still in use today, remains the largest working refractor in the world.

Unfortunately, bigger and thicker lenses sag under their own weight. They also absorb some of the incoming light. These problems, combined with advances in mirror-making, made reflecting telescopes popular again. The 20th century witnessed the rise of large reflectors.

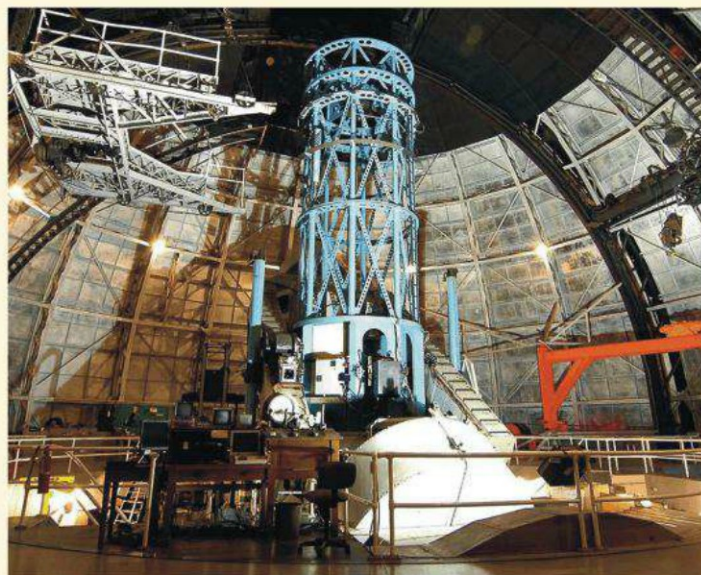
Reflectors return

Astronomers' desire for additional light-gathering power for photography and spectroscopic research helped revive the reflecting telescope. New technology —



DAVE JURASEVICH / MOUNT WILSON OBSERVATORY

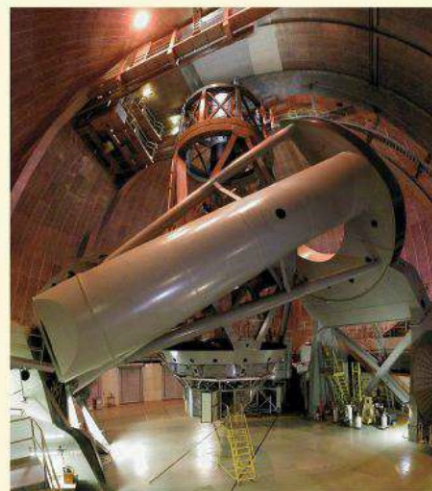
GEORGE ELLERY HALE had the 60-inch glass blank before he secured the funds to build such a telescope. Shortly after the Yerkes refractor was complete, he moved to California, obtained the funding from the Carnegie Institution, and began construction of the 60-inch reflector.



DAVE JURASEVICH / MOUNT WILSON OBSERVATORY

THE 100-INCH HOOKER TELESCOPE joined the 60-inch atop Mount Wilson in 1917. This telescope, another of George Ellery Hale's projects, was the largest in the world until 1948.

THE MASSIVE 200-INCH HALE TELESCOPE was under construction for 21 years. George Ellery Hale, who secured the funding for the 200-inch, passed away in 1938. Almost 1,000 people attended the 1948 dedication of the 200-inch Hale reflector.



DR. T. H. JARRETT (IPAC/CALTECH)

using aluminum-coated mirrors instead of solid metal — meant mirrors required little upkeep. They were also much lighter and more maneuverable. Opticians were building large coated glass reflectors in other countries, but the United States was slow to adopt them. Hale was instrumental in the push toward large reflectors.

Even before the 40-inch Yerkes refractor was complete, Hale began planning a 60-inch reflector. He decided to put the telescope atop Mount Wilson in Southern California, as the Midwest isn't home to the best observing conditions. Hale hired George W. Ritchey, an optician who made high-quality telescope mirrors, including a 24-inch used at Yerkes Observatory. Ritchey's task was to make the 60-inch mirror. He essentially created a "clean room" in his polishing shop: He sealed the windows, kept the temperature as constant as possible, suspended a canvas

screen over the mirror to protect it from dust, and wore a surgeon's cap and gown. In 1908, the 60-inch began operation.

Hale didn't stop there. A few years later, Los Angeles businessman John D. Hooker, along with the Carnegie Institution, provided the money for a 100-inch reflector, also atop Mount Wilson. Upon completion, the entire instrument — mirror, tube, and counterweights — weighed 100 tons, yet could move with great accuracy. The 100-inch Hooker Telescope saw first light in 1917, and regular research began in 1918. After more than 70 years, a new telescope trumped the Leviathan of Parsonstown in size.

Progressively, reflectors got bigger as technology advanced. The Hooker Telescope pushed the weight limit of glass mirrors, so future mirrors used different materials coated with aluminum. The 200-inch Hale reflector at Palomar

Mountain in Southern California held the rank of the largest telescope in the world for almost 30 years, from 1948 until 1975. The Russian Big Telescope Alt-azimuthal, a 236-inch reflector, beat out the Hale Telescope in 1975, but the Hale's optics remained superior. In the 1990s, astronomers built a number of massive reflectors to overtake the Hale's resolving power.

By the end of the 20th century, astronomers were using segmented mirrors to create ever-larger telescopes. Researchers are now building the Giant Magellan Telescope, composed of seven 27.6-foot-wide mirrors, that will be equivalent to a 70.2-foot aperture scope. To overcome atmospheric distortion, they've also launched telescopes into orbit around our planet. The quest to see and understand more about our universe is ongoing. It's a goal set forth more than 400 years ago, and it doesn't show signs of stopping. 🌌

The biggest eyes on the sky

Nearly 50 giant telescopes probe the cosmos from Earth's surface.

by Richard Talcott; graphics by Roen Kelly

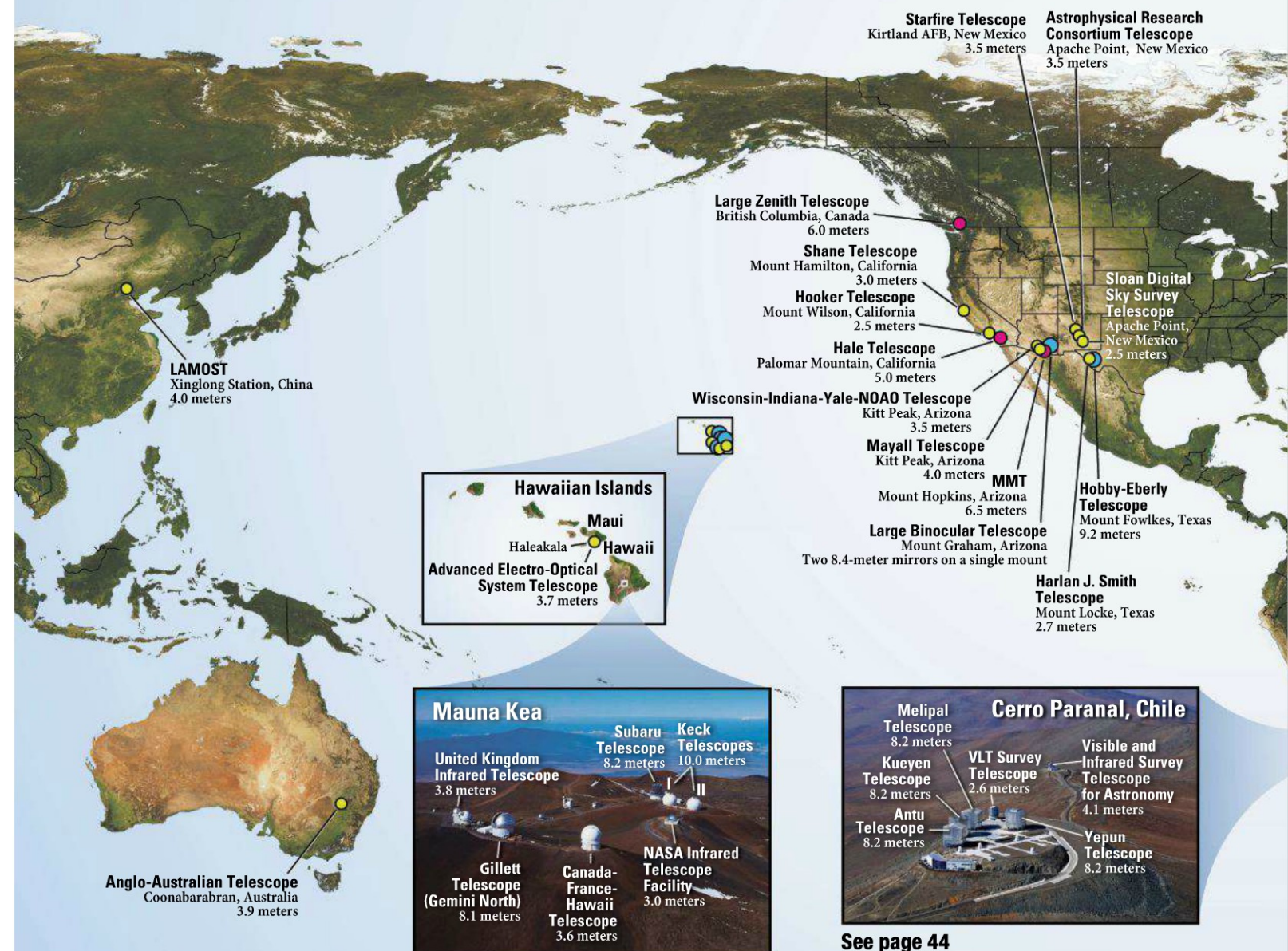
More than 400 years ago, Galileo transformed our view of the universe when he first turned his telescope toward the sky. He saw the Moon as imperfect, four

Richard Talcott is a senior editor of *Astronomy* and author of *Teach Yourself Visually Astronomy* (Wiley Publishing, 2008).

moons circling Jupiter, and Venus going through phases. The great scientist's observations helped overthrow the prevailing scientific beliefs of his time and helped place the Sun in its proper position at the center of the solar system.

And he did it all with a telescope just 1 inch in diameter. Galileo fashioned his

telescope from glass lenses, which refracted the light passing through them to form images. Such refracting telescopes were all the rage among observers until 1668, when Isaac Newton built the first reflecting telescope (like Galileo's, 1 inch in aperture) that used a mirror to gather and focus light.

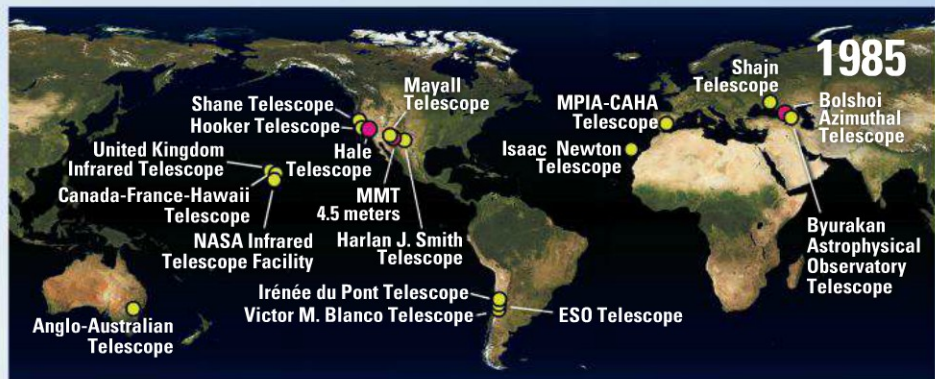


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But small telescopes can do only so much. Bigger scopes collect more light and reveal finer detail. The technology needed to build larger scopes advanced slowly, however. American astronomer George Ellery Hale oversaw construction of the first 100-inch (2.5 meters) telescope in 1917. The Hooker Telescope still stands on Mount Wilson in California, overlooking Los Angeles.

The next record came in 1948 with another Hale project, the 200-inch (5 meters) Hale Telescope on California's Palomar Mountain. By the late 20th and early 21st centuries, big scopes were popping up around the world, mostly on isolated mountaintops where the skies are clear and steady.

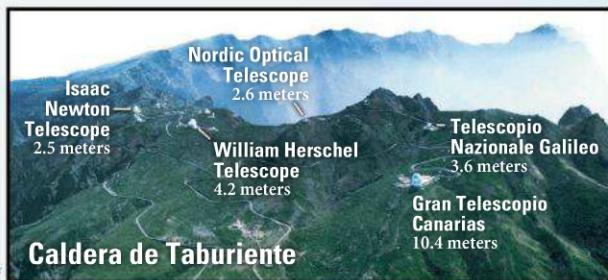


THE BIG EYES a quarter-century ago didn't measure up to today's giant telescopes. In 1985, only two scopes — the Hale and Bolshoi Azimuthal — were 5 meters across. Today, 19 reach that threshold.

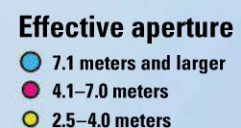
The map below shows the locations of all operating optical and infrared telescopes on Earth at least 2.5 meters in diameter. Note the large concentrations

in Hawaii, Chile, and the Canary Islands. The map above shows big scopes in 1985, a good reminder that we live in a golden age of astronomy. 🌌

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Connecting

AS THE SUN SETS on the summit of Mauna Kea, giant telescopes prepare to observe the heavens — and push back the frontiers of scientific knowledge. LAURIE HATCH

Measured from the ocean's floor, Hawaii's Mauna Kea rises higher than any other mountain on our planet. As solar system volcanoes go, only Olympus Mons on Mars is loftier.

Yet, because Mauna Kea stands a bit more than "waist-deep" in the Pacific Ocean, only 13,796 feet (4,205 meters) of its 32,000-foot (9,750m) stature rises above sea level. But that's enough to pierce the dominating mid-Pacific inversion layer, a point above which clouds seldom form. This boundary generally tops

off between 6,000 and 9,000 feet (1,830m and 2,740m). Because Mauna Kea's peak lies higher, it basks in what is often the clearest, driest, and most stable air our planet has to offer.

It's these circumstances that make Mauna Kea ideal for astronomy. The mountain, already home to many of the largest and most sophisticated telescopes ever to look skyward, is a destination — some might even say a pilgrimage — for lovers of the sky, professional and amateur astronomers alike.

However, before visiting the mountain, its broader human significance bespeaks a

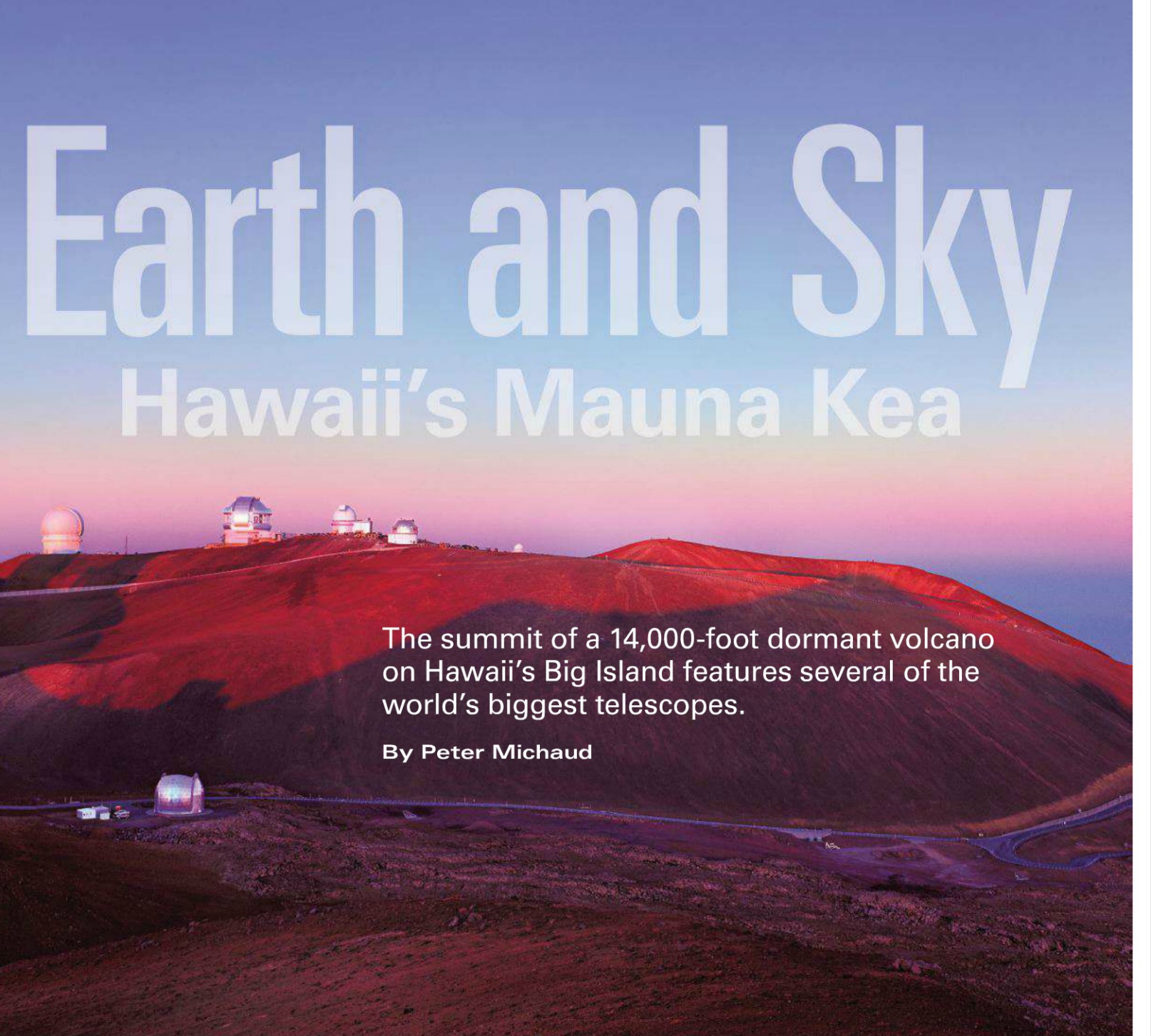
deeper perspective and appreciation. The mountain's obvious physical grandeur overwhelms, often at the expense of its profound human connections.

Mauna Kea: the physical and beyond

Long before anyone gazed upon Mauna Kea's slopes, nature produced what would become an important physical connection to humanity. It took the unlikely combination of a glacier that persisted until about 10,000 years ago and volcanic activity that was last present about 4,500 years ago. Today, volcanologists classify

Earth and Sky

Hawaii's Mauna Kea



The summit of a 14,000-foot dormant volcano on Hawaii's Big Island features several of the world's biggest telescopes.

By Peter Michaud

Mauna Kea as a long-dormant — not extinct — volcano.

When lava emerged beneath the glacial ice, it hardened quickly under pressure from the ice without mixing with surrounding air. This created a dense basaltic rock. Once the first Polynesians arrived, perhaps 1,500 to 2,000 years ago, these explorers quickly discovered this precious rock near the summit. Realizing this material's capacity for attaining and holding a sharp edge, they valued it greatly.

The Hawaiian adz (similar to a modern ax, or hatchet) made from this rock gained a reputation throughout Polynesia

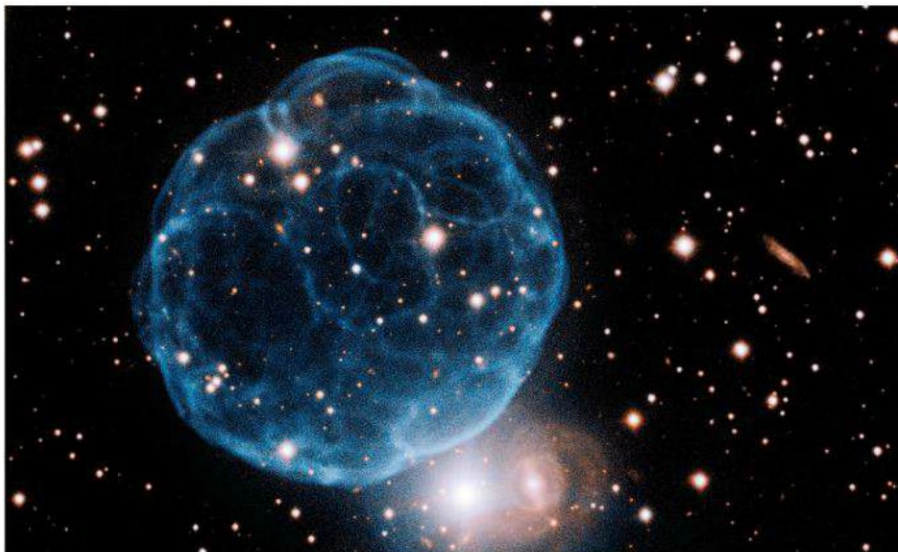
because of its cutting qualities and durability. Used to hollow the hulls of long-distance voyaging canoes, stones quarried by early Hawaiians in the cold, thin air at an elevation of about 12,500 feet (3,800m) now litter the Pacific. This evidence supports the idea that the early Hawaiians traversed this ocean for some time after settling the islands.

Only in the past 40 years have modern non-instrument navigators rediscovered this voyaging tradition and confirmed another connection between the sky and Mauna Kea. Undoubtedly, the sky was critical to how the early Pacific navigators

found their way to and from Hawaii. Given the island's connection to the sky, the concept of piko (Hawaiian for "center") achieved great importance.

A volcanic past

Even to those familiar with the mountain, Mauna Kea's physical presence is so far beyond ordinary experience that it is almost akin to grasping the age or size of the universe. Despite that, Mauna Kea's neighbor, Mauna Loa, is only 117 feet (35.7m) less lofty, but its more gradual slope makes it our planet's most massive volcano and mountain, with Mauna Kea



THE WISPY TENDRILS of planetary nebula Kronberger 61 once belonged to a Sun-like star, which puffed off its outer layers near the end of its life. The Gemini North Telescope captured the glow from doubly ionized oxygen. GEMINI OBSERVATORY/AURA

retaining the title of the tallest (again, as measured from the ocean floor).

Both mountains were born of volcanism. Mauna Loa's most recent activity, in 1984, brought lava from its slopes to within about 5 miles (3 kilometers) of the tropical coastal community of Hilo (where most of the observatories have their headquarters). Nervous residents could see its glow before the eruption subsided. Today, such events occur only at the long-active Kilauea volcano on Hawaii's southeastern flank.

Naturally, building such a significant bump in Earth's crust took time. The island of Hawaii (also known as the Big Island) began forming deep on the ocean floor millions of years ago via an under-sea volcanic hotspot. Over this hotspot, the crust of the ocean floor slides along

Peter Michaud is the public information outreach manager of Gemini Observatory, and is based in Hilo, Hawaii.

toward the northwest at the rate of a fingernail's growth, approximately 0.12 inch (3 millimeters) per month.

Although geologists agree that Mauna Kea will experience volcanic activity in the future, they estimate that its cycle averages roughly 10,000 years. The mountain's long volcanic hiatus makes scientists confident that the telescopes on the mountain are not at serious risk anytime soon from the fires that lie beneath our planet's crust.

Mauna Kea from sunset to starlight

After more than 20 years as a regular guest on Mauna Kea, I'm still moved in ways that I cannot anticipate or even fathom each time I visit its heights.

From the deep, almost blackish-azure of the daytime sky over Mauna Kea, the passage into night is unlike anywhere else on our planet. Looking down on the cloud tops, the setting Sun appears remarkably

brilliant. For the same reason that the inversion layer caps the clouds below, it also confines much of the particulates and moisture to the lower atmosphere. And the world's largest, most diverse, and most technologically advanced community of astronomical observatories takes full advantage of these circumstances.

The dozen observatories on Mauna Kea include four of the largest optical/infrared telescopes on our planet, along with instruments studying radio, millimeter, and submillimeter wavelengths.

"The telescopes of Mauna Kea" on pages 24 and 25 highlights most of the summit's major observatories, which collectively represent a global confluence of scientific research. In addition, three other astronomical instruments call Mauna Kea home.

The Smithsonian Astrophysical Observatory's Submillimeter Array (SMA) is the newest submillimeter telescope on the mountain and was built after the photographer captured the summit photo on pages 24 and 25. The SMA combines the light of eight 6-meter collecting dishes that can be moved to several configurations. (The eight antennas appear in the lower left corner of the panorama on pages 18 and 19.) A powerful correlator in the facility "combines" the light for astronomers to analyze. Astronomers dedicated the SMA in 2003, and it began observing that year. Find out more at www.cfa.harvard.edu/sma.

The Hōkū Ke'a Telescope is the newest on the mountain. The University of Hawaii at Hilo's (UHH) physics and astronomy department runs this 0.9-meter instrument. The telescope, which will be commissioned in 2012, primarily will serve the undergraduate teaching mission of UHH. Students will be the main users and will be able to operate the telescope remotely from an on-campus

THE BARREN SUMMIT of Mauna Kea rises above most of the clouds that bring rain to Hawaii — ensuring exquisite skies on the mountaintop. JEAN-CHARLES CUIILLANDRE (CFHT)

Each clear night at sunset, the [Gemini North] dome's huge vent gates open to dramatically reveal the seven-story 8-meter telescope. When the last rays of twilight wash the telescope, it's a view you don't want to miss.



▲ TWILIGHT COLORS shine through thermal vents in the Gemini North Telescope's dome. The openings help bring the telescope to the outside temperature quickly, thus maximizing observing time. GEMINI OBSERVATORY

► THE DAY'S LAST RAYS of sunlight strike the domes of Gemini North (foreground) and the Canada-France-Hawaii Telescope. JEAN-CHARLES CUILLANDRE (CFHT)

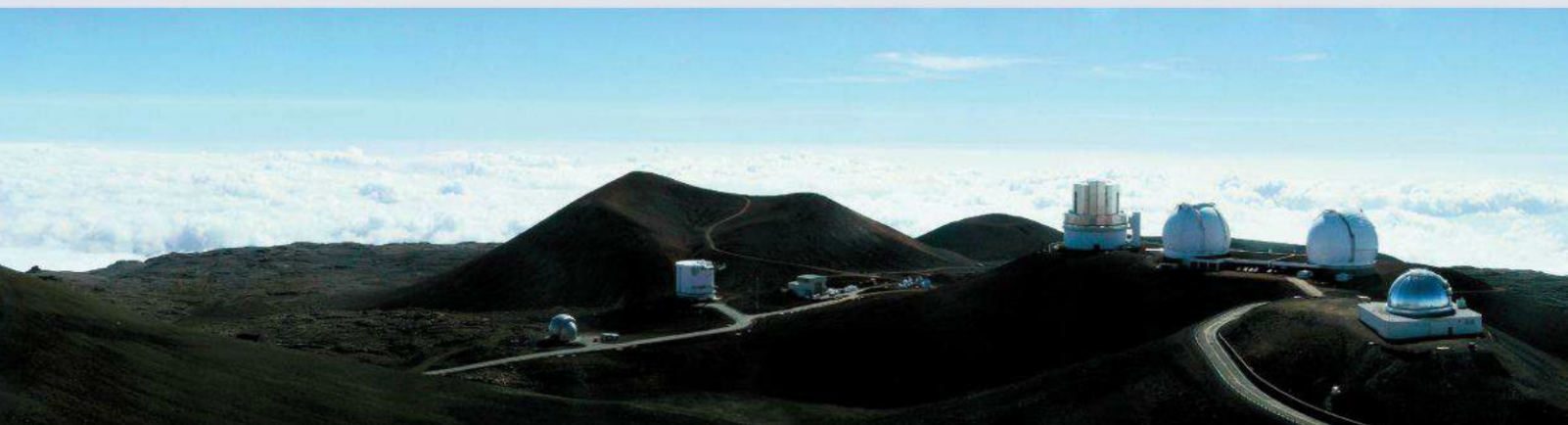
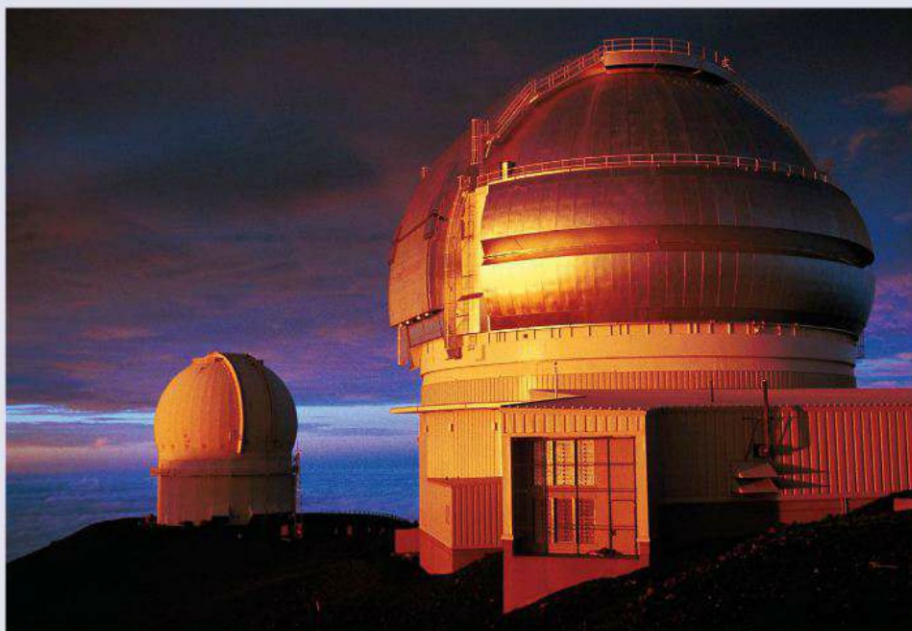
Gemini Observatory North

WEBSITE: www.gemini.edu

TOURS: By appointment only (except during engineering shutdown periods)

TELESCOPE:

- 8.1-meter Frederick C. Gillett Gemini North Telescope





MAUNA KEA CASTS a pyramid-shaped shadow against Earth's atmosphere at both sunrise and sunset. Here, a Full Moon appears inside the shadow. RICHARD WAINSCOT



NGC 253 is one of the brightest galaxies outside the Local Group. Astronomers took this image through the Canada-France-Hawaii Telescope. JEAN-CHARLES CUIILLANDRE (CFHT/COELUM)



Concerns about altitude

Anyone considering a trip to Mauna Kea in Hawaii will have a much better time by following these 10 suggestions.

1) The human body will be uncomfortable at an elevation of nearly 14,000 feet (4,270 meters). Anyone with health issues should check with a doctor before making the trip.

2) Nobody under 16 (or pregnant) should ascend to the summit. Stopping at the Visitors Information Station (VIS) is fine, however.

3) Dress warmly and in layers. Summer daytime temperatures can be comfortable, but at other times it can

get below freezing and feel even colder as your oxygen-deprived body tries to stay warm.

4) Use sunscreen and sunglasses that filter ultraviolet light.

5) Drink lots of fluids and bring food, preferably items high in carbohydrates.

6) Stop, shop, learn, and acclimatize for at least one hour at the VIS on the way up.

7) Rent a four-wheel drive vehicle, but check the terms. Many rental car companies will not allow their vehicles on the Mauna Kea access road. It's dirt for much of the way beyond the VIS, and steep.

8) Use four-wheel drive in low range or all-wheel drive on both the ascent and descent. Excessive braking has caused fatal accidents. This is not a trivial drive for any vehicle.

9) If any health symptoms related to altitude become more than an annoyance, head to a lower altitude immediately. Serious conditions can develop quickly and become life-threatening.

10) Don't try to stay at the summit after sunset. Headlights aren't allowed, and ice (sometimes impossible to see in the dark) can form on the road.

control center. For more information on the UHH physics and astronomy program and the Hōkū Ke'a Telescope, see <http://physastro.uhh.hawaii.edu/NewEducationalTelescope.php>.

The final observatory not mentioned in "The Telescopes of Mauna Kea" is part of the National Radio Astronomy Observatory's Very Long Baseline Array (VLBA). The mountain's only radio dish boasts the largest aperture (25m), but it's not easy to find because it lies 3 miles (5km) below the summit.

This antenna joins with nine others around the globe to form a radio interferometer that provides the greatest resolving power of any telescope. The system began work in 1993. See results from this observatory at www.vlba.nrao.edu.

Science on the mountain

The University of Hawaii (UH) system holds a lease from the state for most of the summit region (11,288 acres) above 12,000 feet (3,658m). In return, each observatory has a percentage of time allocated for use by UH scientists, most of whom are with the university's research unit, the Institute for Astronomy.

Stewardship of the unique cultural and natural resources at the summit is the responsibility of UH-Hilo's Office of Mauna Kea Management (OMKM), which acts in accordance with the UH's 2000 Mauna Kea Master Plan, and a more recently developed and approved Comprehensive Management Plan. All new development must occur within a 525-acre "astronomy precinct."

Mauna Kea Observatory Support Services (funded mostly by the observatories) operates a food and lodging facility and a visitor station. It also provides road maintenance and snow removal (yes, Hawaii has snowplows), and runs a ranger program for OMKM.

In the decades since the first large telescope (the University of Hawaii's 2.2-meter reflector) began collecting starlight above Mauna Kea's sky in 1970, observational astronomy has raced forward. And the discoveries — from the first direct imaging of planets around other stars to revealing the acceleration of the expanding universe and its corollary, dark energy — have shaped our modern view of the cosmos.

— Continued on page 26

The computer-controlled support system for Japan's Subaru Telescope maintains the shape of the largest single-piece primary mirror on Mauna Kea to 1/5,000,000 inch.



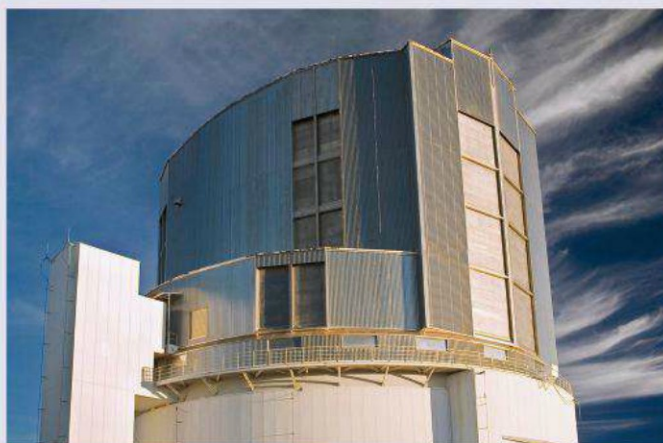
▲ THE SUBARU TELESCOPE'S giant 8.2-meter mirror is the third largest on Mauna Kea (after the two Keck telescopes) and observes both visible and infrared light. "Subaru" is the Japanese word for the Pleiades star cluster (M45). SUBARU TELESCOPE/NAOJ



STAR-FORMING REGION S106 in Cygnus glows strongly at infrared wavelengths, captured here by Subaru. SUBARU TELESCOPE/NAOJ



SPIRAL GALAXY NGC 6946 in Cygnus contains more than 1,000 individual star-forming regions, which appear red in this visible-light image from the Subaru Telescope. SUBARU TELESCOPE/NAOJ



THE UNUSUAL SHAPE of Subaru's "dome" helps the scope reach operating temperature quickly after sunset. SUBARU TELESCOPE/NAOJ

Subaru Telescope

WEBSITE: www.naoj.org

TOURS: Offered up to 15 days each month in Japanese or English at 10:30 A.M., 11:30 A.M., and 1:30 P.M. (reservations required)

TELESCOPE:

- 8.2-meter Subaru Telescope

The telescopes of Mauna Kea

Mauna Kea is home to a dozen observatories; here are some facts about the major ones. Visit each facility's website for more information.

United Kingdom Infrared Telescope (UKIRT)

Beginning operations in 1979, UKIRT is the largest telescope in the Northern Hemisphere devoted entirely to infrared astronomy. Its configuration combines a 3.8-meter mirror and a wide field of view to allow it to image large portions of the sky. One of its surveys has led to many discoveries, such as the most distant quasar. Find out more at www.jach.hawaii.edu/UKIRT.

James Clerk Maxwell Telescope (JCMT)

With a collecting surface of 15 meters, this is the largest telescope in the world dedicated to sub-millimeter observing. Its iconic GORE-TEX membrane, which protects the dish from wind, rain, and dust, allows daytime observing but prevents visitors from seeing the dish from the outside. The JCMT began its long history of discovery in 1987, and today it still remains on the cutting-edge of astronomy with its latest instrument, the Submillimetre Common-User Bolometer Array-2. Details on its work can be found at www.jach.hawaii.edu/JCMT.

University of Hawaii 2.2-meter telescope

As the first significant optical telescope on the mountain, this instrument provided proof that large telescopes on Mauna Kea were not only possible to build and operate, but also that they would perform exceptionally well. With first light in 1970, the University of Hawaii 2.2-meter scope now serves primarily for graduate research. You'll find more of its history at www.ifa.hawaii.edu/88inch.

Gemini Observatory North Telescope

A seven-country partnership consisting of the United States, Canada, England, Australia, Brazil, Argentina, and Chile built and operate this 8.1-meter optical/infrared telescope. Together with its twin in Chile, the two scopes can observe the entire sky. Gemini North began scientific operations in 2000. Explore its latest data at www.gemini.edu.

Caltech Submillimeter Observatory (CSO)

Upon arrival near the summit, the CSO is one of the first telescopes you'll see, and arguably the most distinctive. Its geodesic dome, clad with reflective aluminum, houses a 10.4-meter dish used for observations of short millimeter and submillimeter radiation. The CSO's dome is sometimes opened during the daytime, making it possible to glimpse the telescope, operational since 1986, when driving by. You'll find out more at <http://cso.caltech.edu>.



Subaru Telescope

The National Optical Astronomy Observatory of Japan operates this 8.2-meter optical/infrared telescope. Like Gemini, it uses a one-piece mirror and is one of the largest optical/infrared telescopes in the world. Operations began in 1999 from within its distinctive cylindrical enclosure, which moves with the telescope. Public tours require advance reservations. See details at www.naoj.org.

W. M. Keck Observatory

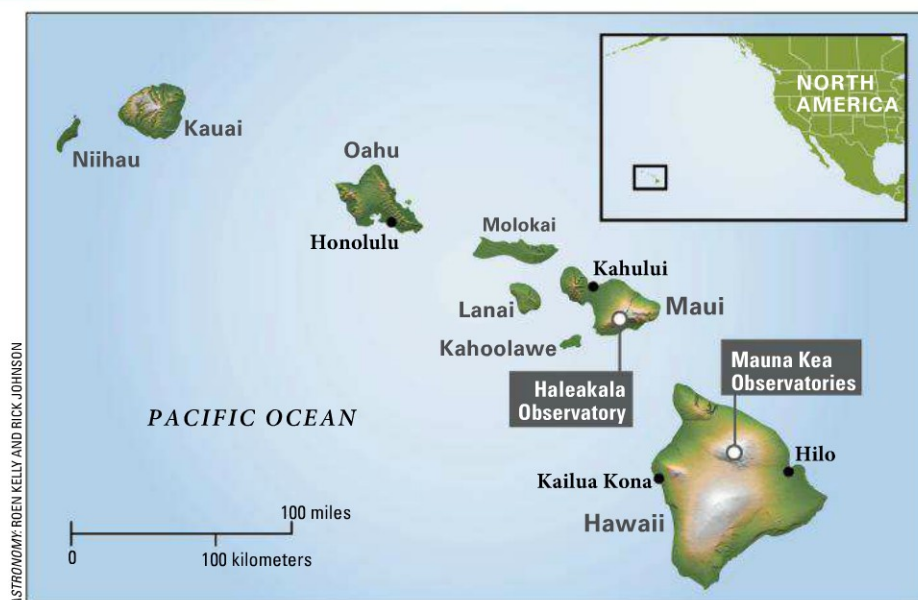
The twin Keck telescopes rank in the top three of Earth's largest optical/infrared telescopes. Each uses segmented mirrors to produce an aperture of 10 meters. The two instruments link as an interferometer to provide high-resolution data. Keck I (left) began operations in 1993, and Keck II saw first light in 1996. A visitor's gallery and telescope viewing area are open to the public. Learn more at www.keckobservatory.org.

Canada-France-Hawaii Telescope (CFHT)

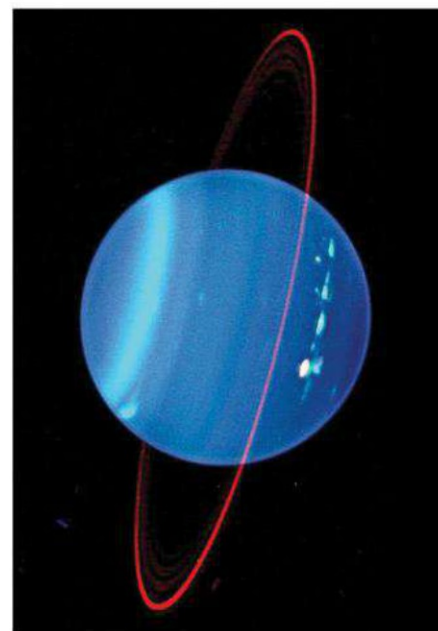
This 3.6-meter optical/infrared telescope was the first on Mauna Kea to break the 3-meter threshold when it opened in 1979. CFHT provided much of the groundwork that led to the adaptive optics systems used today on Mauna Kea's 8- to 10-meter telescopes. Its large field also produces stunning images, which you can see at www.cfht.hawaii.edu.

NASA Infrared Telescope Facility (IRTF)

Another of the "old-timers" on the mountain, the IRTF was built to support NASA's planetary space missions. It has, however, proven itself useful well beyond its original "scope" and purpose. It turned its 3-meter mirror skyward in 1979, and this telescope still actively monitors our solar system and various cool stars. See <http://irtfweb.ifa.hawaii.edu>.



HAWAII BOASTS some of the world's finest weather — for astronomers and vacationers. Mauna Kea on the Big Island rises above 40 percent of Earth's atmosphere, where the air is clear, dry, and stable. Conditions on Maui's Haleakala are nearly as good.



THE PLANET URANUS and its rings stand out in this infrared image from Keck.

— Continued from page 22

And they are not likely to stop soon. Currently, astronomers have developed plans for the Thirty Meter Telescope (TMT), which will sit on the mountain's northern plateau (although construction is still pending as this article goes to press). The power of the TMT's huge segmented mirror, which will operate in wavelengths ranging from the ultraviolet to the mid-infrared, will be integral to the next epoch of astronomical discovery.

Experiencing Mauna Kea firsthand

Visiting these facilities is not a trivial matter. For those who overcome the challenges of getting to the top independently (see "Concerns about altitude" on page 22), it's important to know what to expect because of limited public accommodations. The one exception is the visitors

gallery and Keck I viewing area at the W.M. Keck Observatory, which is open most days. Check the observatory's website at www.keckobservatory.org to confirm times. In addition, Japan's Subaru Observatory provides tours, but advance reservations are necessary. Schedule online at www.naoj.org.

For those not inclined to reach the summit on their own, each evening licensed commercial tour companies guide visitors (thousands per year) to the ridge adjacent to the mountain's actual summit. From this vantage point, most of the observatories are visible, adorned with the warm glow of the setting Sun to soften the chill of the high-altitude air.

The most intimate and dramatic view from this ridge is of the nearby Gemini North Telescope. Each clear night at sunset, the dome's huge vent gates slide open to dramatically reveal the seven-story

8-meter telescope. When the last rays of twilight's glow wash the telescope, it's a view you don't want to miss.

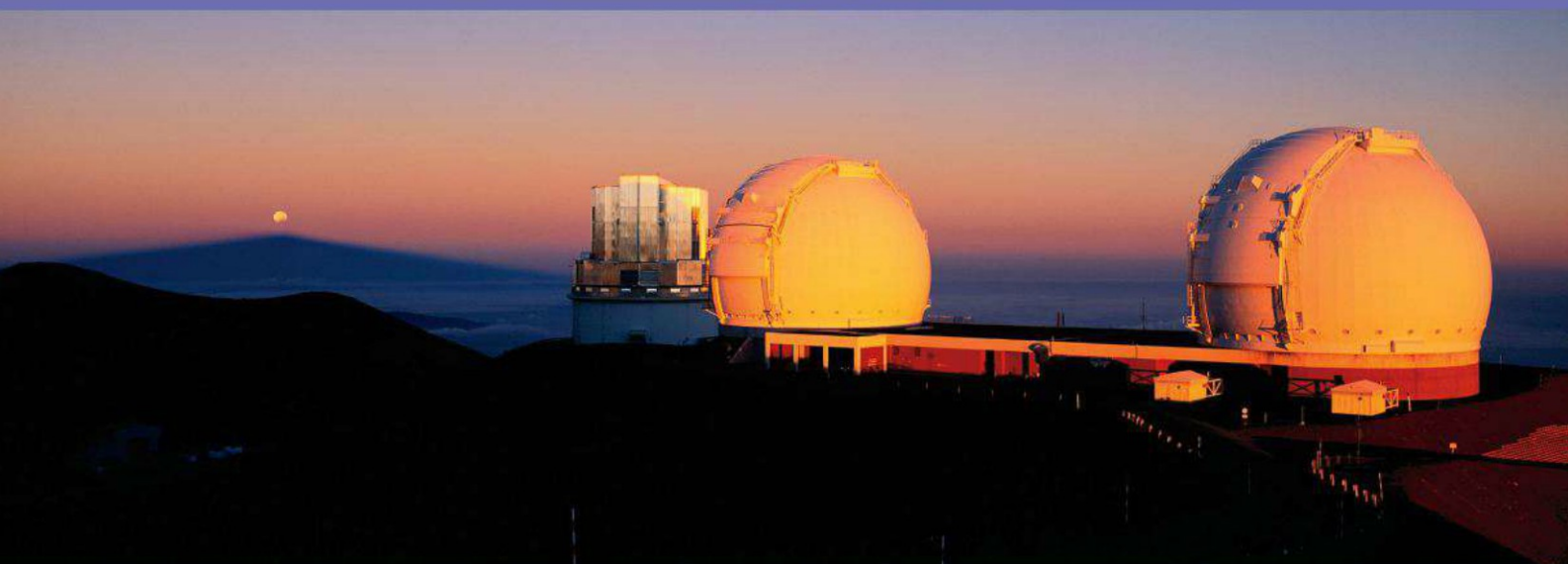
Commercial tours generally provide a basic stargazing experience using medium-sized high-quality telescopes. Serious amateurs, however, will want to consider all stargazing options.

Logging eyepiece time

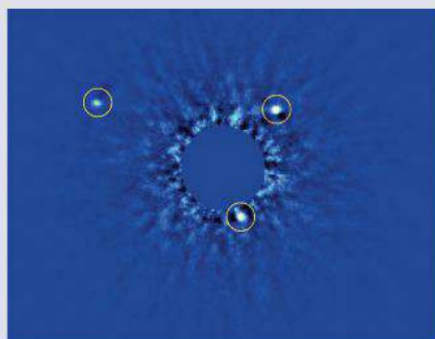
When it comes to hard-core observing, many amateurs find it difficult to believe that the summit area is among the *least favorable* places on the mountain to view the sky. There are the obvious reasons: cold temperatures, lack of shelter, and difficult management of bodily functions. But the primary reason for not observing "on high" is physiological. The human eye simply doesn't perform well when the atmospheric pressure pushes 40 percent less oxygen into your blood. For most

WHITE AND SILVER DOMES contrast with volcanic rocks at the summit. This 180° panorama shows Mauna Kea's north and east ridges. JEAN-CHARLES CUILLANDRE (CFHT)

The adaptive-optics system at Keck Observatory uses a 6-inch mirror that changes its shape up to 1,000 times per second to cancel out atmospheric distortion. Images are 10 times sharper than without the system.



THE TWIN DOMES of the Keck telescopes (with Subaru behind them) greet the rising Sun on July 16, 2000. The Moon, which is emerging from a total lunar eclipse, stands just above the pinnacle of Mauna Kea's shadow being cast onto Earth's atmosphere. RICHARD WAINSCOT



KECK AND GEMINI combined to take the first direct image of a multiplanet system beyond our own. The three planets (circled) orbit the star HR 8799; scientists removed its light to reveal the planets.

GEMINI AND KECK OBSERVATORIES/NRC/AURA/CHRISTIAN MAROIS, ET AL.

W. M. Keck Observatory

WEBSITE: www.keckobservatory.org

VISITORS WELCOME: 10 A.M. to 2 P.M.

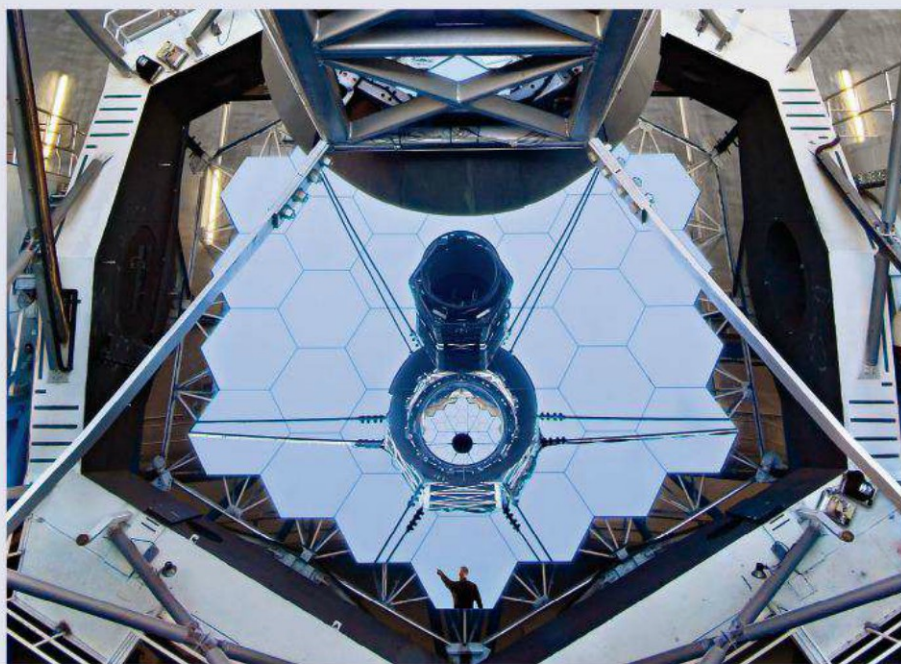
Monday–Friday (observatory headquarters);

10 A.M. to 4 P.M. Monday–Friday

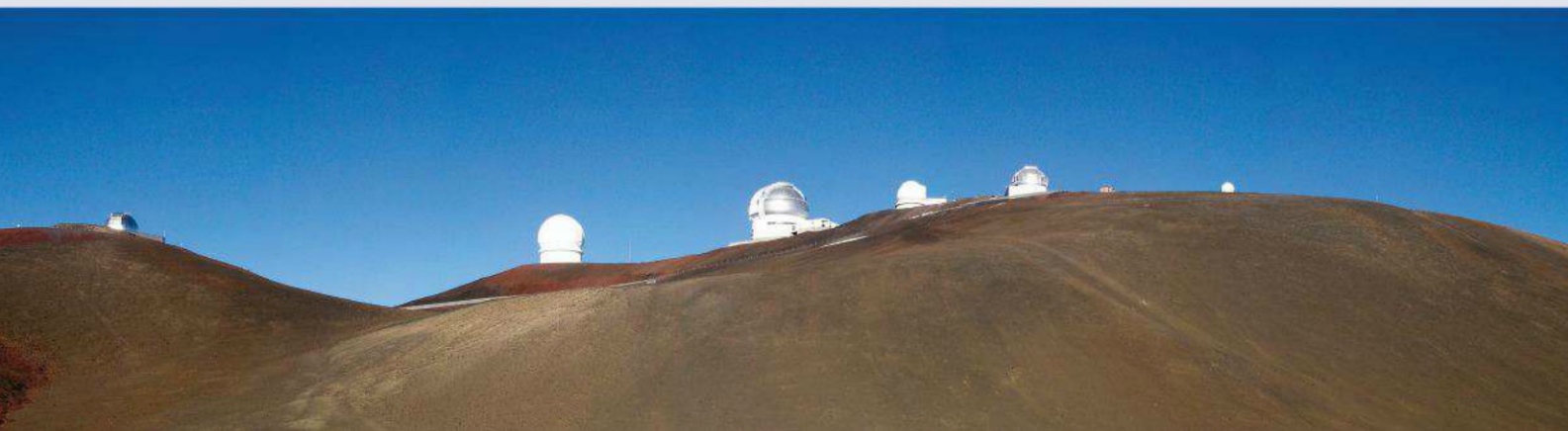
(visitor's gallery)

TELESCOPES:

- 10-meter Keck I and Keck II telescopes



THE KECK II TELESCOPE MIRROR (above), like its Keck I twin, consists of 36 hexagonal segments, each of which is 6 feet (1.8 meters) across and weighs 880 pounds (400 kilograms). The telescope itself contains 270 tons of steel. LAURIE HATCH





Beyond Mauna Kea

For astro-tourists making the pilgrimage to Hawaii, Mauna Kea is literally and figuratively the pinnacle. However, more peaks can fill your itinerary — and your eyes — with starlight.

Mauna Loa

When traveling up the Big Island's Saddle Road, look to the south for the only slightly less lofty Mauna Loa. Even a casual glance reveals the different shades of gray from eruptions that have spilled our planet's innards over its slopes.

Just above the 11,000-foot (3,353 meters) level of Mauna Loa lurks a diverse collection operated by the National Oceanic and Atmospheric Administration. These include a solar telescope, instruments to monitor atmospheric aerosols and ozone, and the mountain's most famous experiment: the continuous record of atmospheric carbon dioxide (CO₂). Going back to 1958 when Charles David Keeling took the first CO₂ measurements, these data are central to today's global-warming debate.



THE FIRST PAN-STARRS TELESCOPE, with its 1.8-meter mirror, lies 10,023 feet (3,055 meters) above sea level on the summit of Maui's dormant volcano, Haleakala. ROB RATKOWSKI/PAN-STARRS

For all of its history and diversity, Mauna Loa is not a popular destination. First, the route stretches about 18 miles (29 kilometers) from Saddle Road, and maintenance is an issue. Second, there are few amenities, and the facilities are small. The view of Mauna Kea is exceptional, however, and, for the ambitious, that alone makes it worth the effort.

Haleakala

The highest peak on nearby Maui is home to a community of observatories as

well. At an altitude of "only" 10,023 feet (3,055m), access to Haleakala is easy on a well-maintained road. A visitor-friendly national park sits at the top, and a variety of hikes and stunning vistas makes Haleakala a must-do for visitors to the island.

The University of Hawaii's Institute for Astronomy, the U.S. Air Force, and others run facilities that are part of the "Science City" on the summit. The National Solar Observatory's New Technology Telescope will soon join them. While these

buildings cannot accommodate visitors, the national park provides everything you should need.

Absorbing the day's first solar rays from Haleakala is one of the most popular activities anywhere in Hawaii, and if you arrive early enough you'll have a chance to see stars, too. In addition, the Maui Astronomy Club holds monthly star parties on the mountain and welcomes visitors to share in the viewing. Visit the club's website at www.mauiastronomyclub.org.



HAWAII ISN'T ALWAYS BALMY. Winter storms can bring snow to Mauna Kea, but crews keep the roads open so astronomers can reach the telescopes. DERRICK SALMON (CFHT)

people, the result is a milky-looking, washed-out sky with a naked-eye magnitude limit verging on abysmal.

To combat lightheadedness, cold, and lack of oxygen, renowned visual observer and *Astronomy* Contributing Editor Stephen James O'Meara experimented with a drastic technique. Called pressure breathing, he claims it can overcome the lack of mental alacrity and visual acuity at high altitude. According to O'Meara, his experimentation at the summit allowed him to eventually see the Andromeda Galaxy (M31) as well as he did from lower elevations, but he adds, "I've spied my

faintest naked-eye stars from the 9,000-foot level, not the summit."

Seeing on the mountain

As with O'Meara, the conventional wisdom among stargazers on the mountain puts the sweet spot for observing at about 9,000 feet (2,740m). As I mentioned, this is typically where the inversion layer comes into play. It's also the location of UH's Ellison Onizuka Visitors Information Station (VIS, pronounced "viz").

David A. Byrne, who manages the VIS, adds that the 100,000 or so visitors per year who make the journey to that level

For skywatchers accustomed to a more northern perspective, the Hawaiian sky offers far too many treasures to list.

for stargazing experience “the best sky on our planet.” He adds that his staff of paid and volunteer interpretive guides conduct the free nightly stargazing programs, and the Mauna Kea Rangers have responsibilities for health and safety.

“The rangers have responded to situations ranging from altitude sickness to serious vehicle accidents,” says Byrne. “The mountain can be a dangerous place for the unprepared, and we try to anticipate people’s mistakes.”

The VIS snuggles amid a small village containing astronomers’ quarters, road and building maintenance equipment, offices, and storage buildings. For serious amateurs, observing here takes some patience. But don’t despair. The large early evening crowds will disperse, the headlights shining in your eyepiece will disappear, and you eventually will be alone among the stars. The wait will be worth it.

In the meantime, the display of public enthusiasm for stargazing at the VIS should hearten anyone who loves to share the sky. Open year-round, solar viewing happens during the day, and evening stargazing begins as twilight fades.

By 9 P.M., most of the crowds have dwindled to the most serious (and warmly dressed) stargazers, many with their own scopes. The VIS staff and volunteers will retire their 10 or so telescopes (with up to 16-inch apertures) as the remaining visitors warm up to hot chocolate and astronomical gift shopping in the small shop.

Visitors on the Saturday closest to each month’s New Moon, however, have a good chance of meeting up with the local astronomy club. Its members will share their views with other friendly stargazers well into the night. Omiyage (O-me-ya-ge), a local (Japanese) tradition of giving small gifts of gratitude, is appreciated by the amateur astronomers who welcome you for stargazing with the “aloha” that Hawaii is famous for.

Stargazers who want to bring their own equipment will appreciate that the VIS has a pair of mounts on piers that will fit many popular 8-inch telescopes. The outside observing patio also is always available. And there are restrooms.

For skywatchers accustomed to a more northern perspective, the Hawaiian sky offers far too many treasures to list. A few of my favorites include the constellation Crux the Southern Cross; the nearest star



MAUNA KEA’S SUMMIT rises above the clouds, affording astronomers clear views. A First Quarter Moon illuminates the landscape in this photo. GEMINI OBSERVATORY



OBSERVERS MARVEL at the sky from the Ellison Onizuka Visitors Information Station at the 9,000-foot (2,740 meters) level on Mauna Kea. Guests there can view the Sun during daylight and stargaze after twilight fades. JOSHUA WILLIAMS

system, Alpha (α) Centauri; the biggest and brightest globular cluster, Omega Centauri (NGC 5139); and, my personal favorite, the zodiacal light. While this last sight is not unique to Hawaii, most experienced skywatchers marvel at how bright this wedge of natural light appears in the western evening and eastern morning sky.

A final reflection

As the first Polynesians gazed upon Mauna Kea, photons from the most distant easily

visible naked-eye stars began racing toward this improbable astronomical destination. Ultimately, these photons mingled with more-seasoned travelers, who told of even stranger storied pasts from the edge of the observable universe.

Some photons, captured for study by the modern telescopes atop Mauna Kea, enlighten us with knowledge. Most, however, absorbed by the mountain, are manifest in the piko that connects Earth, sky, and humanity. ☾

GREAT obser

Large telescopes make great destinations for astronomy enthusiasts.

By Douglas Isbell



C

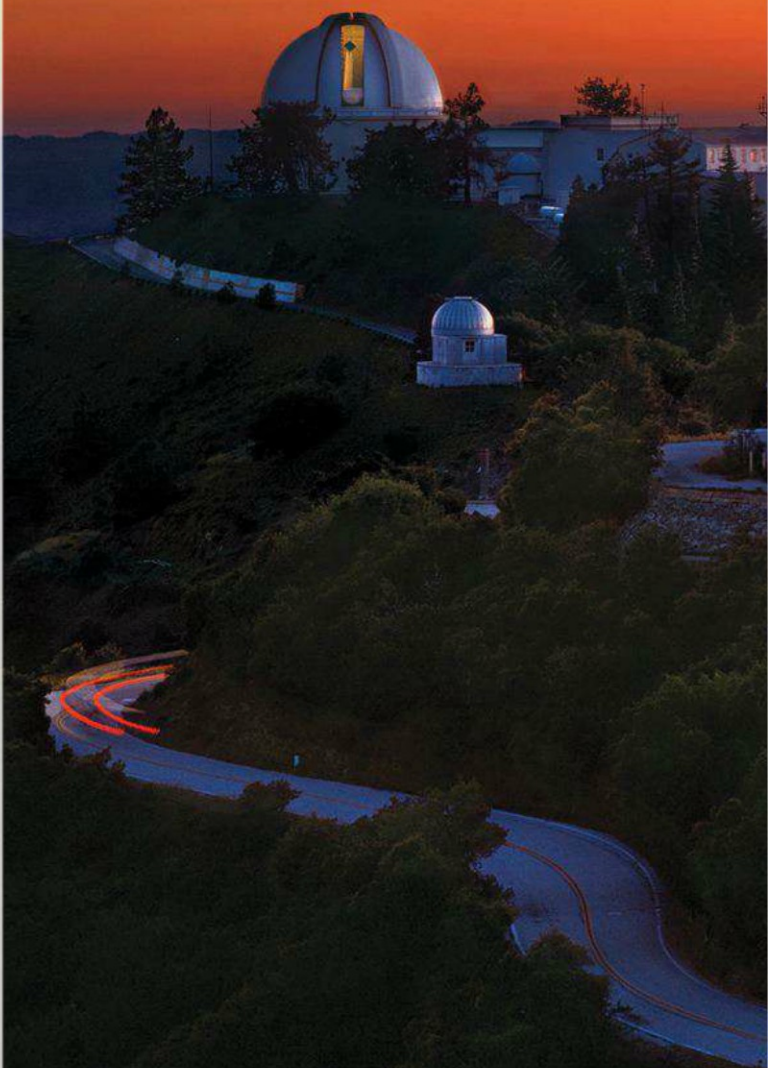
onsistently clear, dark skies. Geographic convenience. The timely confluence of major advancements in technology and economic might with a rapidly maturing scientific field.

These are the major forces that created the incomparable band of astronomical observatories ringing Texas, New Mexico, Arizona, and California in the United States. Although many of their roots reach back east to the woods of Wisconsin and cities in Massachusetts, it is the physical and societal feat of building and operating these observatories that is the dominant story of the first 80 years of 20th-century astronomy. (At least until a certain durable space telescope and the strange colliding phenomena of dark matter and dark energy came along — but more on that later in this publication.)

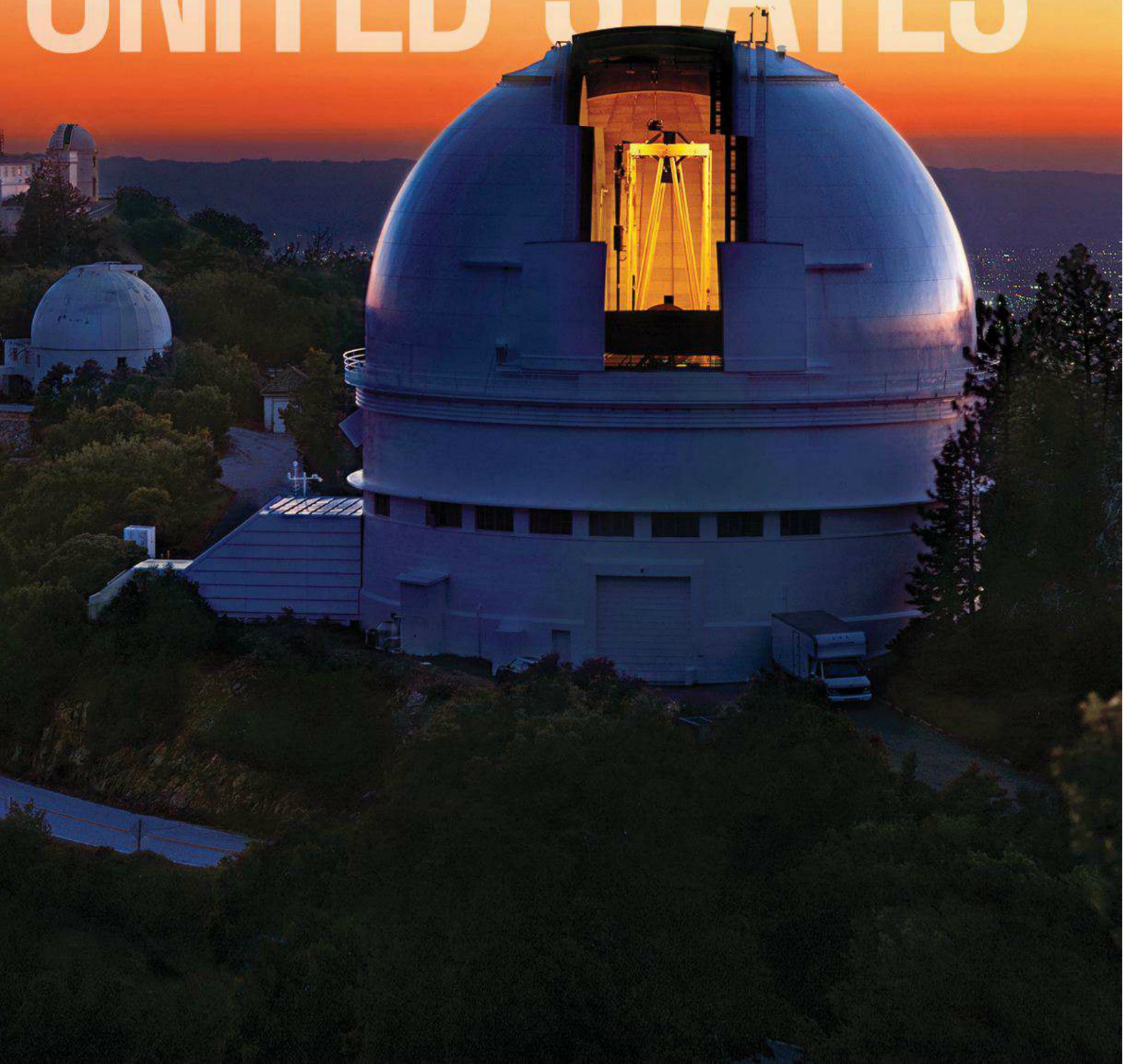
Even better, a dedicated traveler can visit many of these sites in a focused week of travel. No matter where you start, you'll find a bounty of sights and sounds, stirred by history and natural wonders, to enjoy many times over.

Douglas Isbell *has worked in communications related to space exploration and astronomy for more than 20 years, and is co-author of The Observatories of the Southwest: A Guide for Curious Skywatchers (University of Arizona Press, 2009).*

THE TELESCOPES OF LICK OBSERVATORY prepare for a night's work. The 120-inch Shane Reflector (foreground) is the site's largest, while the 36-inch Lick Refractor (back left) is its most historic. LAURIE HATCH



Observatories of the UNITED STATES



McDonald Observatory

LOCATION: Davis Mountains, Texas

WEBSITE: <http://mcdonaldobservatory.org>

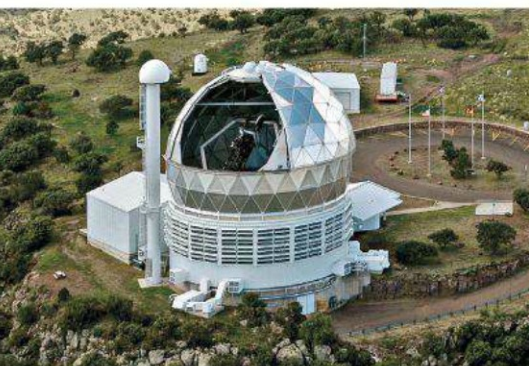
VISITORS WELCOME:

10 A.M. to 5:30 P.M. daily

TOURS: 11 A.M. and 2 P.M. daily (reservations required)

TELESCOPES:

- 9.2-meter Hobby-Eberly Telescope
- 2.7-meter Harlan J. Smith Telescope
- 2.1-meter Otto Struve Telescope



THE HOBBY-EBERLY TELESCOPE sits on Mount Fowlkes in Texas' Davis Mountains. MARTY HARRIS/MCDONALD OBSERVATORY

Bigger in Texas

Davis Mountains, Texas

Perhaps the most sensible exploration route begins in the plains of West Texas. Back in the 1930s, influential astronomy pioneers (and World War I veterans) Gerard Kuiper and Otto Struve applied their high-society connections from the University of Chicago in Illinois and lessons learned from the builders of Yerkes Observatory in southern Wisconsin to build and run a supreme dark-sky observatory in the Davis Mountains, which was dedicated in 1939.

Located north of Big Bend National Park near the small town of Fort Davis (which retains some of its original charm as an isolated outpost of the Old West), McDonald Observatory today is dominated by the giant Buckminster Fuller-like Hobby-Eberly Telescope (HET). A marvel of efficient design, the segmented mirror of the 11-meter telescope sits at a fixed elevation level while its instrument package at prime focus moves to track the sky. This technique reduces the effective diameter of the HET to 9.2 meters, but it makes such an instrument less costly to build and maintain. A small crew hand-assembled the struts of the HET's massive geodesic dome in just a few days before they promptly lowered them into place by crane.

THREE LARGE TELESCOPES dominate McDonald Observatory. The 2.7-meter Harlan J. Smith Telescope (right) and 2.1-meter Otto Struve Telescope rule the foreground while the 9.2-meter Hobby-Eberly Telescope stands out at back left. MARTY HARRIS/MCDONALD OBSERVATORY

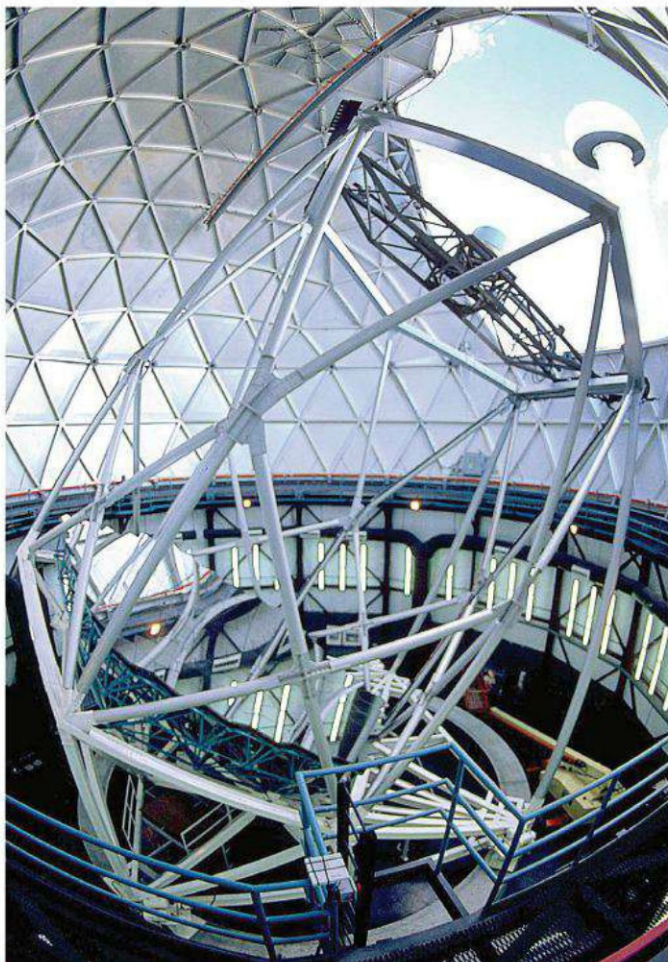
Dedicated in 1997, the HET is optimized for spectroscopy. It therefore logs extensive time studying the light signatures of solar system objects, stars in the Milky Way, and extragalactic objects; it also is involved in the search for exoplanets.

The two daily tours at McDonald Observatory don't go inside the historic 2.7-meter Harlan J. Smith Telescope, built in the late 1960s in part to serve as "eyes" on the solar system. Still, the observatory lobby has an exhibit about the scope and its namesake, the observatory's longtime director. This instrument is available to rent for private viewing parties, making it one of the largest telescopes accessible to the public.

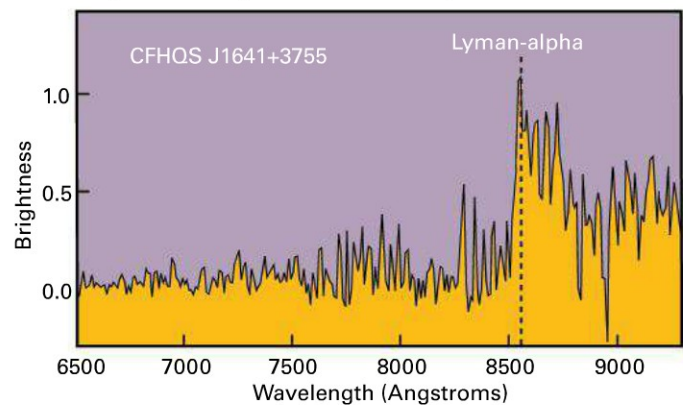
The McDonald staff, with its modern visitor center, regularly hosts large public star parties three times a week at its small public observatories, including a new lunar-viewing program that uses a 16-inch telescope. Its most intriguing new offering is the handicap-accessible 18-inch Wren-Marcario Accessible Telescope; originally designed for supernovae hunting, the telescope went through a reconfiguration with the help of the Las Cumbres Observatory Global Telescope Network and was re-dedicated in 2010. ☼



Set your sights on America's great observatories



Hobby-Eberly dissects a quasar



▲ A SPECTRUM of the quasar CFHQS J1641+3755 taken with the Hobby-Eberly Telescope reveals the object's enormous redshift. Light from hydrogen gas has stretched from 121.6 nanometers to more than 850nm. GARY HILL/TIM JONES/MCDONALD OBSERVATORY

◀ THE 11-METER SEGMENTED MIRROR of the Hobby-Eberly Telescope points at a fixed elevation, which reduces its effective diameter to "only" 9.2 meters. It excels at taking spectra of the cosmos.

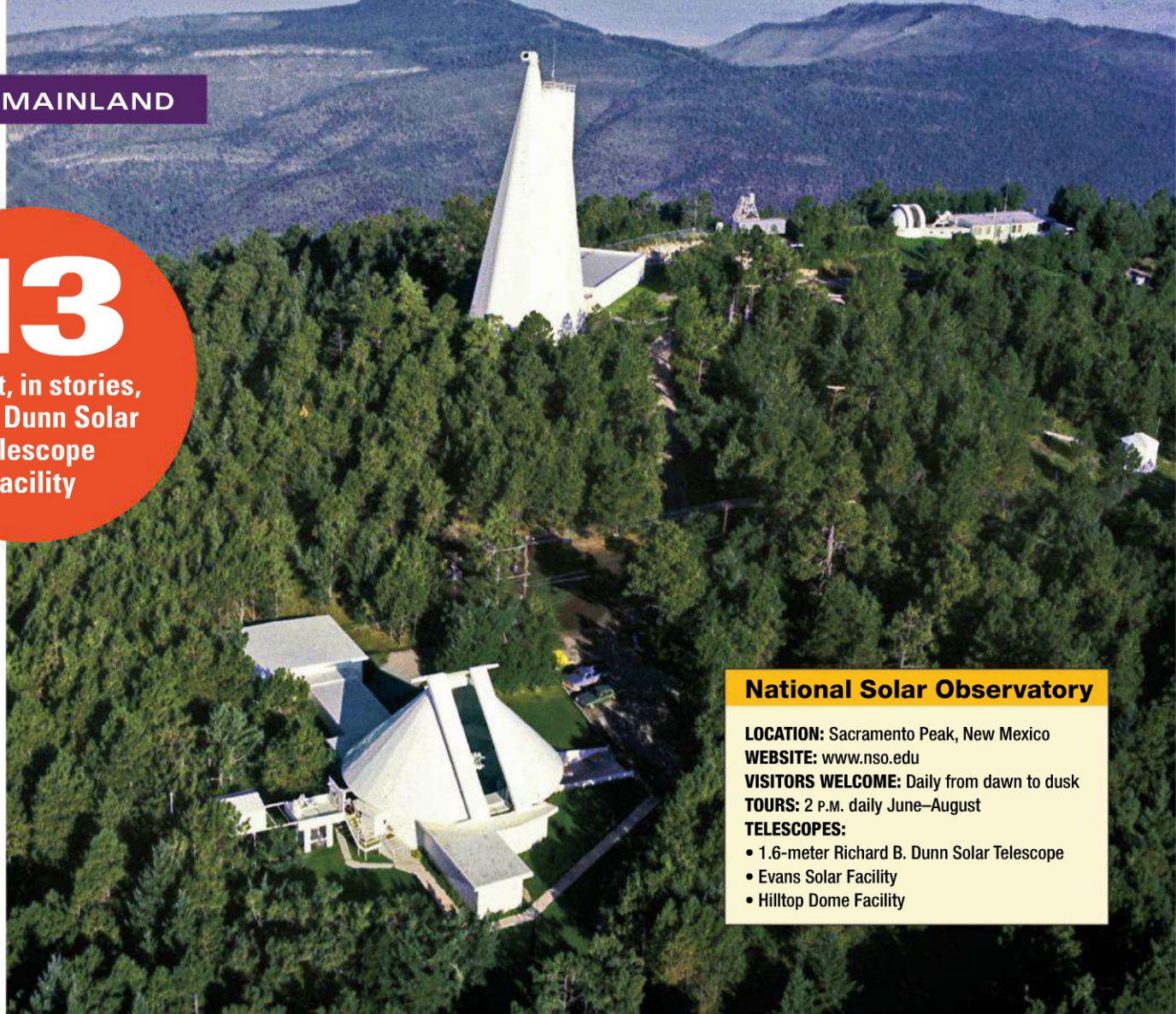
THOMAS A. SEBRING/MCDONALD OBSERVATORY

91

Number of hexagonal segments in the Hobby-Eberly Telescope mirror

13

Height, in stories,
of the Dunn Solar
Telescope
facility



National Solar Observatory

LOCATION: Sacramento Peak, New Mexico

WEBSITE: www.nso.edu

VISITORS WELCOME: Daily from dawn to dusk

TOURS: 2 P.M. daily June–August

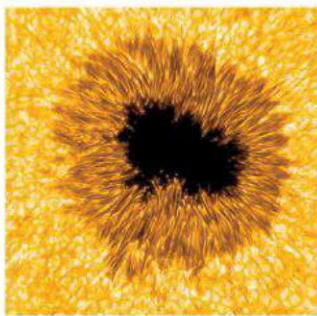
TELESCOPES:

- 1.6-meter Richard B. Dunn Solar Telescope
- Evans Solar Facility
- Hilltop Dome Facility

THE DUNN SOLAR TELESCOPE towers over the other instruments on Sacramento Peak. The Evans Solar Facility lies in the foreground of this photo while the Hilltop Dome Facility appears at top right. NOAA/AURA/NSF

New Mexico's twin peaks

Sacramento Peak and Sunspot, New Mexico



ADAPTIVE OPTICS allows the Dunn Solar Telescope to achieve a resolution of 0.14 arcsecond and capture incredible detail. This sunspot spans about three times Earth's diameter. FRIEDRICH WOEGER (KIS)/CHRIS BERST AND MARK KOMSA (NSO/AURA/NSF)

If you finish touring McDonald in the early afternoon, you would have enough time to drive comfortably to lodging in Alamogordo, New Mexico. Once there, you can visit Sacramento Peak, home to one of two sites of the National Solar Observatory (NSO). It also hosts the Sloan Digital Sky Survey telescope and the Astrophysical Research Consortium 3.5-meter telescope at Apache Point Observatory.

At nearly 10,000 feet (3 kilometers) and a significant

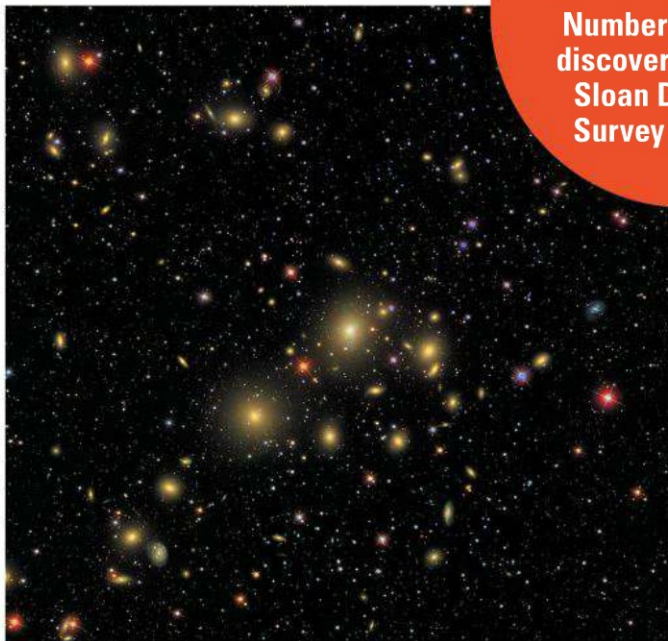
climb from the nearby town of Cloudcroft, the tiny outpost of Sunspot, New Mexico, was a world unto itself for the early pioneers who first lived there; they imported a grain bin purchased from Sears, Roebuck and Co. to house their early solar-observation instruments. NSO-Sunspot's showpiece is the vaguely pyramidal 1960s Richard B. Dunn Solar Telescope, which resembles a rocket deposited by an unknown ancient civilization.

Rising 13 stories above ground and extending 1.6

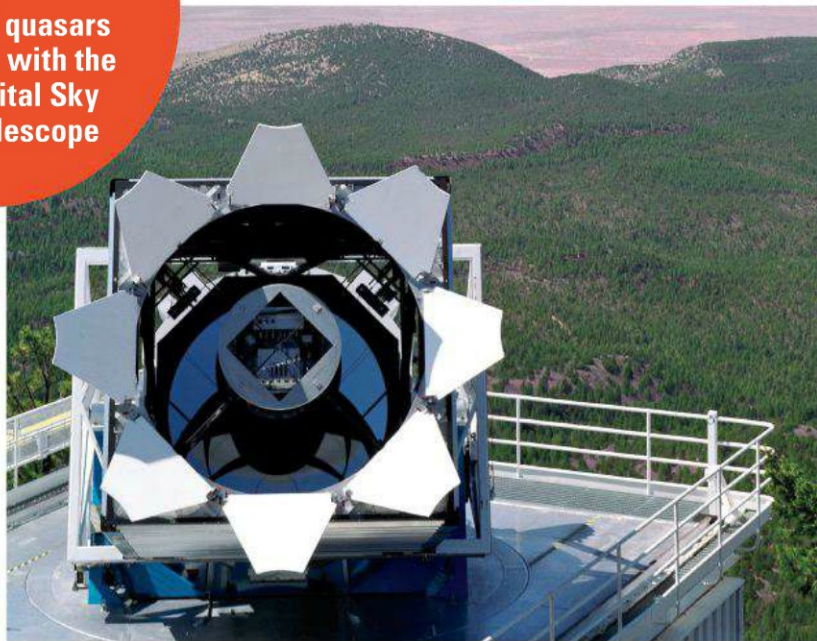
times that below, this evacuated tower gathers sunlight through a steerable turret at the top and directs it toward a 1.6-meter primary mirror, which then is able to project a 20-inch-wide (51 centimeters) image of the solar disk. The Dunn has been a pioneer of using adaptive optics during the daytime — reaching into infrared wavelengths — to observe the intriguing large-scale granulation of the solar surface that appears to drive so many of its complex processes.

120,000

Number of quasars
discovered with the
Sloan Digital Sky
Survey telescope



THE SLOAN DIGITAL SKY SURVEY has scanned one-third of the visible night sky. This image shows the Perseus galaxy cluster, with NGC 1275 near center. R. LUPTON & THE SDSS COLLABORATION, WWW.SDSS.ORG



THE 2.5-METER TELESCOPE used to conduct the Sloan Digital Sky Survey resides at Apache Point Observatory in New Mexico's Sacramento Mountains. FERMILAB VISUAL MEDIA SERVICES

The NSO offers guided tours of the Dunn and its other facilities each afternoon in the summer months starting from a simple but informative visitor center. However, a self-guided walking tour is inspiring in itself, and it's also a great way to see the neighboring Apache Point Observatory.

The 2.5-meter Sloan Digital Sky Survey (SDSS) telescope sits perched at the western edge of the Apache Point summit inside a modest

house-like structure, which rolls back to reveal this amazing workhorse. Now conducting its third major batch of sky surveys, the SDSS telescope has observed one-third of the visible night sky in awesome detail, mapping nearly a billion galaxies in three dimensions and discovering more than 120,000 quasars. Its biggest public outreach image to date contains more than a trillion digital pixels, equivalent to the view of a half-million high-definition TV screens.

Meanwhile, the Astrophysical Research Consortium 3.5-meter telescope at Apache Point is one of the lesser-known large telescopes in North America. Its primary mirror was an important prototype of the rotating hot oven process used by the University of Arizona's Steward Observatory Mirror Lab, which the university continues to use today in service of the pending Large Synoptic Survey Telescope and Giant Magellan Telescope.

Dedicated in 1994, the Apache Point 3.5-meter is owned and operated by a consortium that includes New Mexico State University, the University of Chicago, the University of Washington, Princeton University, and Johns Hopkins University, whose researchers often use the telescope remotely. Among its scientific claims to fame is a role in monitoring the laser-ranging reflectors left on the Moon by the Apollo astronauts. ☛

Apache Point Observatory

LOCATION: Sunspot,
New Mexico

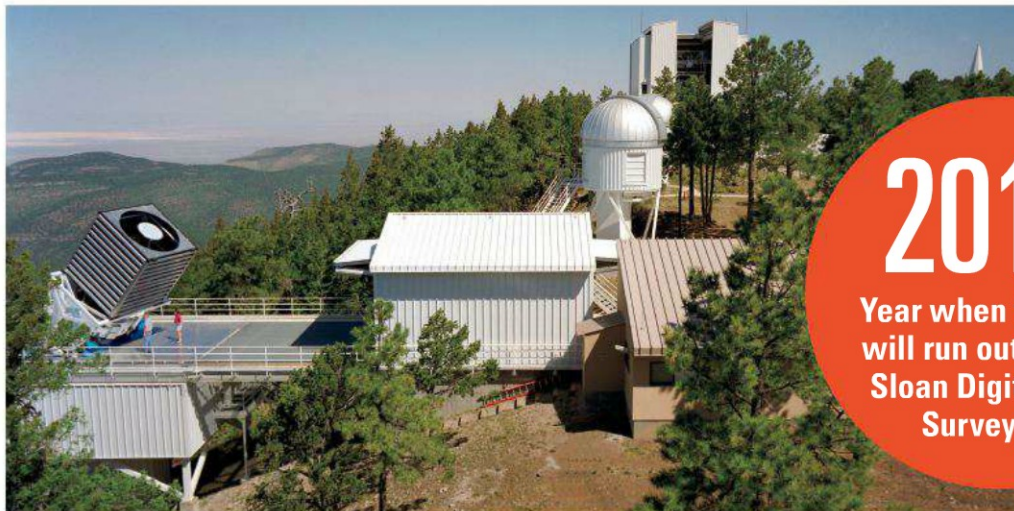
WEBSITE: www.apo.nmsu.edu

VISITORS WELCOME: 7 A.M. to
5 P.M. daily

TOURS: 9 A.M. and 1 P.M.
Monday–Friday (reservations
required)

TELESCOPES:

- Astrophysical Research Consortium 3.5-meter telescope
- Sloan Digital Sky Survey 2.5-meter telescope
- New Mexico State University 1.0-meter telescope



APACHE POINT OBSERVATORY features the 3.5-meter Astrophysical Research Consortium telescope (far building) and the 2.5-meter Sloan Digital Sky Survey telescope (left). FERMILAB VISUAL MEDIA SERVICES

2014

Year when funding
will run out for the
Sloan Digital Sky
Survey-III



Mount Graham International Observatory

LOCATION: Mount Graham, Arizona

WEBSITE: <http://mgio.arizona.edu>

VISITORS WELCOME:

9 A.M. Friday and Saturday,
mid-May to mid-November
(reservations required)

TELESCOPES:

- Large Binocular Telescope
- 10-meter Heinrich Hertz Submillimeter Telescope
- 1.8-meter Vatican Advanced Technology Telescope

THE LARGE BINOCULAR TELESCOPE on Mount Graham in southern Arizona boasts two 8.4-meter mirrors in the same support structure. When working together, the pair gathers as much light as a single 11.8-meter mirror. AARON CERANSKI/LARGE BINOCULAR TELESCOPE CORPORATION



THE CRAB NEBULA (M1) is a supernova remnant — debris from a massive star that exploded. Researchers took this image with one of the Large Binocular Telescope's mirrors. VINCENZO TESTA, ET AL. (ROME OBSERVATORY)/LARGE BINOCULAR TELESCOPE CORPORATION

Two eyes on the mountain

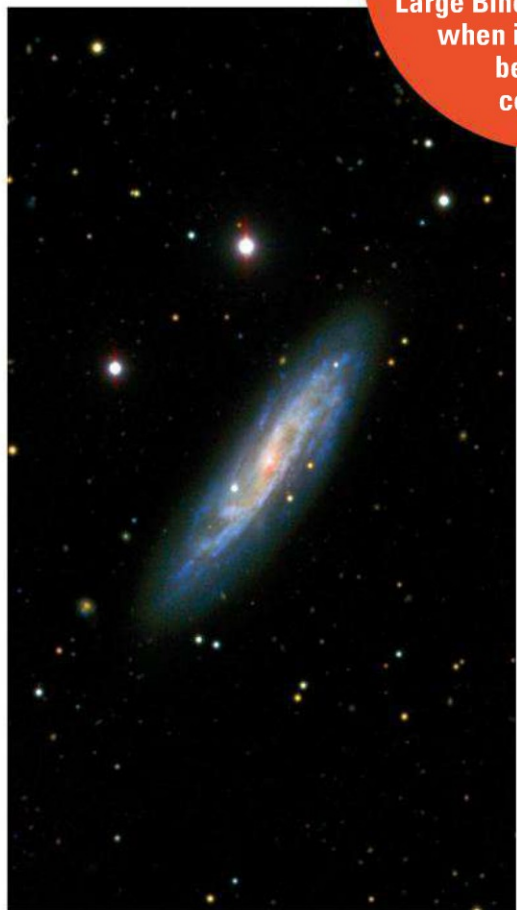
Mount Graham, Arizona

White Sands National Monument beckons to the west of Sacramento Peak, but the true astronomical tourist may be too intent on reaching the cactus-strewn bounty of southern Arizona to pause long.

It may be somewhat surprising to encounter the most powerful ground-based telescope on Earth (and one that is likely to keep this title for another 10 years or so) — the gargantuan Large Binocular Telescope (LBT) — in the middle of the desert Southwest. The LBT at Mount Graham International Observatory near Safford, Arizona, consists of two primary mirrors, each 8.4 meters in diameter, set next to each other in the same massive mounting structure. This complicated facility took more than eight years to reach its full maturity in 2005, and nearly two

22.8

Resolution, in meters, of the Large Binocular Telescope when its two mirror beams are combined

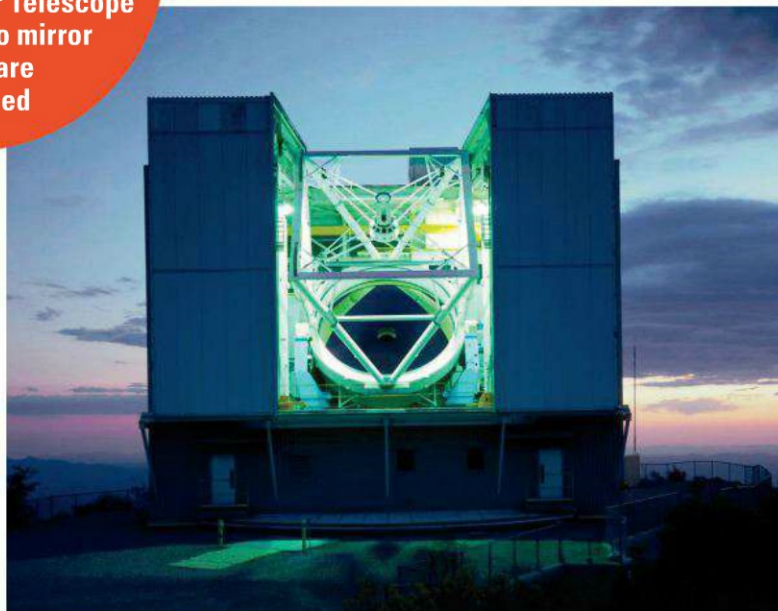


GALAXY NGC 2770 was among the Large Binocular Telescope's first targets in binocular mode. VINCENTO TESTA, ET AL. (ROME OBSERVATORY)/LARGE BINOCULAR TELESCOPE CORPORATION

decades before that to move from concept to construction, due to environmental concerns about Native American land use and a protected population of red squirrels on Mount Graham.

Today, the LBT's two mirrors routinely work together, whether by observing the same object with red- and blue-filtered cameras that benefit from the equivalent light-gathering power of an 11.8-meter mirror, or by combining their beams using interferometry to yield the resolution of a single 22.8-meter-wide instrument.

The Discovery Park Campus of Eastern Arizona College in Safford is the home base for advance-reservation public tours of Mount Graham from mid-May to mid-November, which includes a 40-mile (64km) drive over a steep, curvy access road that is not fit for the easily queasy. The summit also yields views of a productive submillimeter-wave radio telescope and the 1.8-meter Vatican Advanced Technology Telescope, an observing outpost of the Vatican Observatory. A view (or even a mention) of this sleek corrugated metal facility always sparks interesting discussions about the nature of the interaction between science and religion. ☞



THE 6.5-METER MIRROR of the MMT gets ready for a night's work at the Whipple Observatory on Mount Hopkins in southern Arizona. HOWARD LESTER/MMTO

All around Tucson

Mount Hopkins, Arizona

Although the city of Tucson, Arizona, lies a few hours farther west, it is the likely home base for visitors to the Large Binocular Telescope because it also sits at the epicenter of the greatest collection of observatories to be found anywhere.

Many great people, from Gerard Kuiper in the 1960s to Bart Bok in the 1970s to Roger Angel today, helped establish and foster Arizona's observatories, but perhaps none is a greater character than Fred Lawrence Whipple. Fresh from his groundbreaking observations of space satellites and the dips in their orbits that scientists can use to infer Earth's shape, Whipple wished to provide his staff at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, with a clear, dark site to fuel a need for new data. He and his colleague Nicholas Mayall — remember that name — located Mount Hopkins in Arizona during visual scouting trips in a small airplane in 1966.

Roughly halfway between Tucson and the border with Mexico, the Fred Lawrence Whipple Observatory has endured everything from massive snowstorms during construction to Border Patrol issues to the looming development of an open-pit copper mine. This facility has remained on the cutting-edge of optical astronomy by transforming its biggest instrument, the MMT, from a hybrid assembly of six 1.8-meter mirrors that Whipple creatively obtained from the U.S. Air Force in 1979 into a single-mirror 6.5-meter telescope.

Whipple Observatory

LOCATION: Mount Hopkins, Arizona
WEBSITE: www.cfa.harvard.edu/flwo
VISITORS WELCOME: 8:30 A.M. to 4:30 P.M. Monday–Friday
TELESCOPES:

- 6.5-meter MMT
- 1.5-meter Tillinghast reflector
- 1.3-meter PAIRITEL reflector
- 1.2-meter reflector
- VERITAS
- Hungarian-made Automated Telescope network
- MEarth array

Kitt Peak National Observatory

LOCATION: Kitt Peak, Arizona

WEBSITE: www.noao.edu/kpno

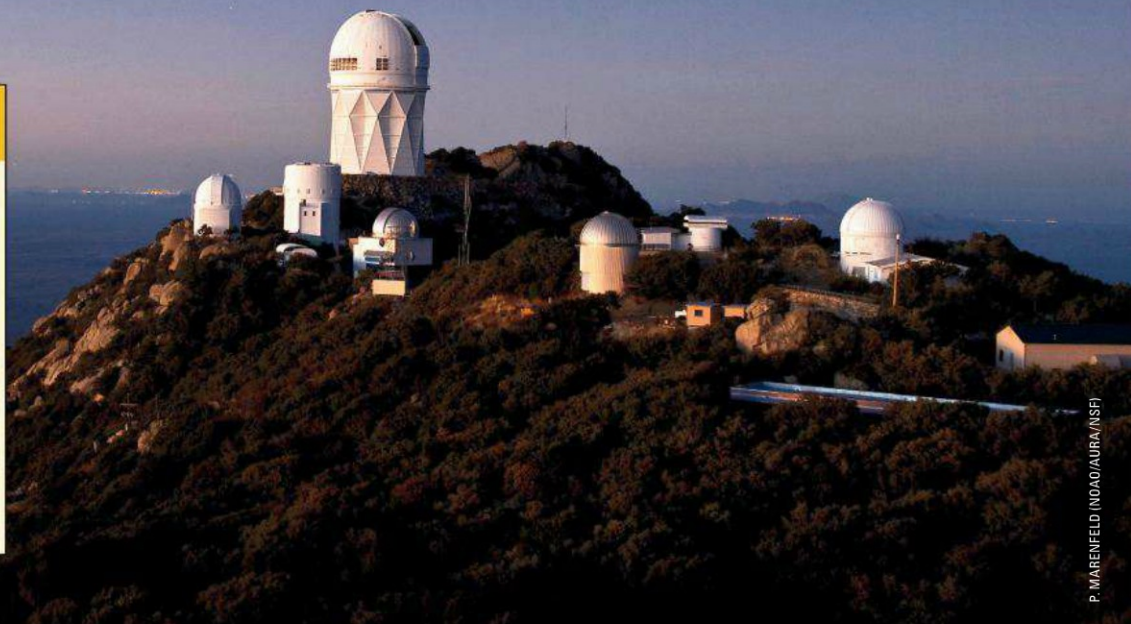
VISITORS WELCOME:

9 A.M. to 4 P.M. daily

TOURS: 10 A.M., 11:30 A.M., and 1:30 P.M. daily

TELESCOPES:

- 4-meter Nicholas U. Mayall Telescope
- 3.5-meter WIYN Telescope
- 2.1-meter reflecting telescope
- 1.6-meter McMath-Pierce Solar Telescope



P. MARENFIELD (NOAO/AURA/NSF)

THE HUGE DOME of the 4-meter Nicholas U. Mayall Telescope rises above the Kitt Peak National Observatory's other instruments.

The observatory is also famous for its leading work in ground-based gamma-ray astronomy. This specialty continues today with the four-telescope Very Energetic Radiation Imaging Telescope Array System (VERITAS), one of which is visible near the visitor center, complete with explanatory signage. These 12-meter dishes observe the “shower” of secondary energy produced in Earth’s upper atmosphere by incoming high-energy radiation from objects such as the Crab Nebula (M1).

The Whipple visitor center was recently bolstered with models of the original and converted MMT and a 3-foot by 18-foot (0.9m by 5.5m) image of the night sky produced by the Sloan survey. With luck, summit tours will resume in spring 2012.

Whipple’s colleague and friend Mayall was a local expert in the peaks of the Sonoran Desert thanks to his experience as operational director of Kitt Peak National Observatory, located 56 miles (90km) southwest of Tucson. Funded primarily by the National Science Foundation (NSF), Kitt Peak was founded in 1958 thanks to the political skills of a collection of moderately sized, mostly Midwestern universities that were eager for their own access to dark skies.

After a review of more than 150 sites and 11 finalists in Arizona, New Mexico, and California, the group chose a mountain known to the local Tohono O’odham Nation as the sacred peak “Ioligam.” The two sides negotiated a relatively modest lease agreement, bolstered by economic and educational support for the Native American tribe, and construction of two 0.9-meter telescopes soon began, followed by a 2.1-meter and then the iconic 4-meter Nicholas U. Mayall Telescope.

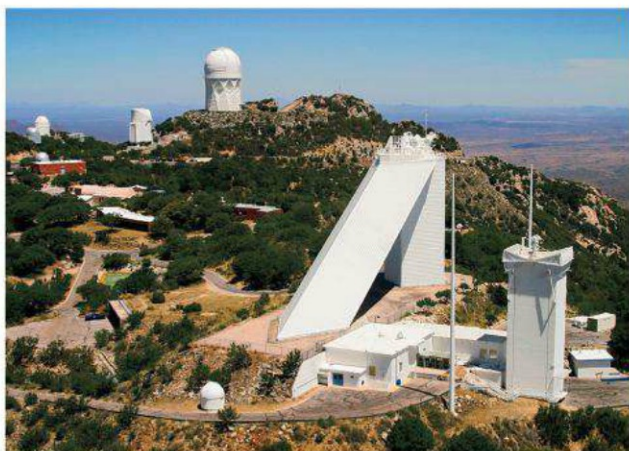
The majestic Mayall was the second-largest telescope in the world in 1970 when completed atop Kitt Peak. It still continues to attract highly competitive observing proposals from around the world, and operators may transform it into a giant spectrographic machine called the Baryon Oscillation Spectroscopic Survey (BigBOSS) in the coming years, should the NSF and the U.S. Department of Energy provide sufficient funds.

Meanwhile, the newest and second-largest instrument at Kitt Peak is the 3.5-meter WIYN Telescope. Dedicated in 1994 and pronounced “win,” the observatory is operated by the WIYN Consortium, which consists of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories. The WIYN Telescope is one of the most versatile imaging scopes in the world because it includes a CCD camera with a 10-arcminute field of view, an infrared imager, a bench spectrograph, and an optical instrument that creates 1-gigapixel images of WIYN’s 1° field of view, which is key for wide-field surveys.

Kitt Peak is also home to the world’s largest solar telescope, the angular 1.6-meter McMath-Pierce, which is the linchpin of the second major site run by the National Solar Observatory (NSO). Beyond its landmark work dissecting sunspots, the McMath is famous for its use in training many of the Apollo astronauts in the visual features of the Moon that some of them would see up close. But its 50-year-old claim as the world’s largest will continue for only a few more years until the NSO completes the 4-meter Advanced Technology Solar Telescope in Hawaii and decamps its institutional headquarters from Tucson to Boulder, Colorado.



THE 3.5-METER WIYN TELESCOPE on Kitt Peak boasts a 1° field of view and ranks among the world’s most versatile imaging telescopes. NOAO/AURA/NSF



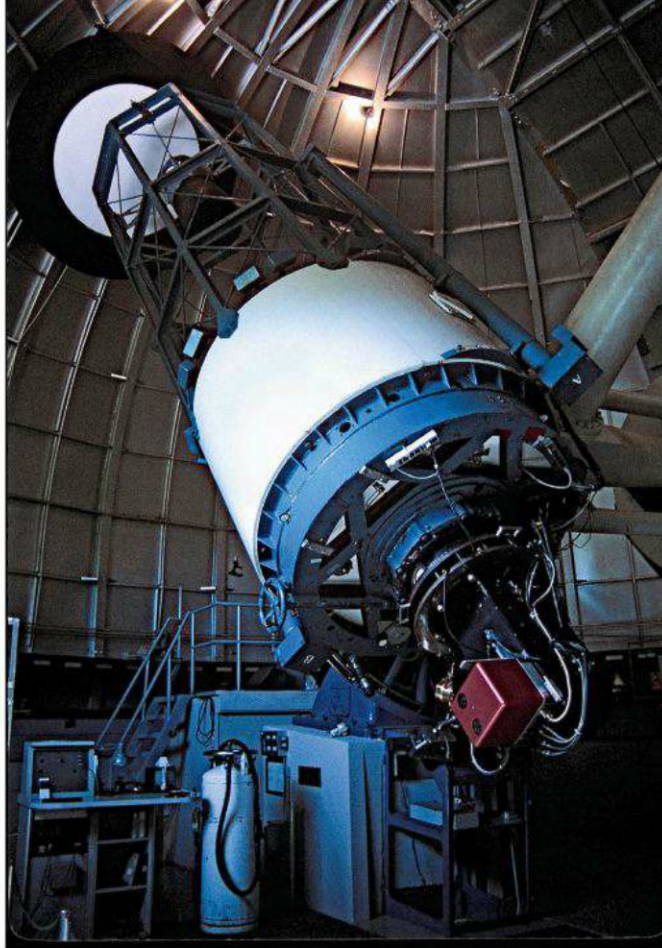
THE DIAGONAL SHAFT and vertical support of the 1.6-meter McMath-Pierce Solar Telescope stands front and center in this aerial view of Kitt Peak. NOAO/AURA/NSF



THE DUMBBELL NEBULA (M27), a planetary nebula in the constellation Vulpecula, represents the final stages in a Sun-like star's life. Astronomers captured this image through Kitt Peak's 3.5-meter WIYN Telescope. GEORGE JACOBY, WIYN/NSF

Kitt Peak conducts one of the more active public outreach programs in ground-based astronomy, hosting daily hourlong tours of each major facility as well as a V.I.P. tour of the entire mountain that lasts up to five hours. Paid groups of four to five dozen people can visit most nights (except during the summer monsoon season) for a light dinner, a lecture, binocular observing, and then guided viewing through one of three large amateur telescopes. An advanced program where amateurs can take their own digital images in an overnight session with a guide is also available. (One of the major popularizers of the Kitt Peak Nightly Observing program, Adam Block, now operates a similar effort on Mount Lemmon, northeast of Tucson, using a newly obtained 32-inch telescope as part of an interesting pairing of astronomy outreach with ecology education called the Mount Lemmon SkyCenter.)

**1
BILLION**
Number of pixels in an
image produced by the
WIYN Telescope



THE 72-INCH PERKINS TELESCOPE currently ranks as the largest at Arizona's Lowell Observatory, but the 4.3-meter Discovery Channel Telescope soon will surpass it. ROBERT BURNHAM

Arizona-dark skies

Mount Hopkins, Arizona

The observatories of the Tucson region remain impressively productive despite the encroachment of residential lighting and other developments stretching north some 100 miles (160km) to the Phoenix metro area, thanks in large part to the dedicated effort of the locally based International Dark-Sky Association.

The world's first dark-sky-certified city lies 150 miles (240km) north of Phoenix in Flagstaff, Arizona, home of the legendary Lowell Observatory. Thanks to its eccentric founder, the wealthy

Bostonian Percival Lowell, and his passion for comets and the murky "canals" of Mars, Lowell is home to the first scientific instrument known to have lived in the Arizona territory. This small telescope on Mars Hill, smack dab in the middle of Flagstaff, began operation in 1896 but was soon superseded by the now historic 24-inch Alvan Clark Telescope, with its conical dome that originally rotated on rubber truck tires.

Whether it's looking through the Clark Telescope on public observing nights or seeing the 13-inch telescope and blink comparator used by Clyde Tombaugh to discover Pluto in 1930, a visit to Lowell, with its elaborate rotunda

Lowell Observatory

LOCATION: Flagstaff, Arizona**WEBSITE:** www.lowell.edu**VISITORS WELCOME & TOURS:**

Varies by day and month

TELESCOPES:

- 4.3-meter Discovery Channel Telescope (under construction)
- 72-inch Perkins Telescope
- 42-inch John S. Hall Telescope
- 24-inch Alvan Clark Telescope
- 13-inch Pluto Discovery Telescope
- Navy Optical Interferometer

STARS WHEEL ABOVE the rotunda at Lowell Observatory. The building houses Percival Lowell's library and other historical exhibits. GEOFF CHESTER

building and recently remodeled visitor center, always delivers a special combination of the quirky history and unique spirituality of astronomy (including Percival Lowell's tomb, which resides on Mars Hill and is reminiscent of both an observatory dome and the night sky).

A private staff of about 15 astronomers at Lowell continues to do world-class work in areas such as stellar variability, star formation, and Kuiper Belt objects at its Mars Hill and Anderson Mesa locations. (The latter includes the Navy Optical Interferometer, a collaborative effort among the U.S. Naval Observatory, the Naval Research Laboratory, and Lowell Observatory.) Meanwhile, the observatory works to put the final touches on the 4.3-meter Discovery Channel Telescope (DCT), nearly complete at a site called Happy Jack, 45 miles (72km) southeast of town. The new workhorse will be able to make spectroscopic and imaging observations at the same time. As of this writing, the DCT was on schedule for first light in May 2012. Hopefully, active public tours of the telescope will be available one day. ☼



SUNSET BATHES the dome of the 200-inch Hale Telescope on Palomar Mountain as a waxing gibbous Moon looks down on the scene. SCOTT KARDEL (PALOMAR OBSERVATORY)

SoCal sites

Southern California

The ambitious astronomical enthusiast can now turn west toward the three major professional observatories of California: by size, start in San Diego; by history, Los Angeles; by sheer physical beauty, San Francisco.

From its graceful but impossibly huge white dome to its gray battleship-like size, the 200-inch Hale Telescope at Palomar Observatory, 70 miles (110km) north of San Diego, is arguably the greatest icon

of ground-based astronomy. Built over more than a decade of frustrating work, split by World War II, and finally ready for scientific use in 1949, the 200-inch Hale (named after George Ellery Hale, the tormented genius of 20th-century observatory construction) is an engineering marvel. Its massive 14.5-ton primary mirror was a technological celebrity long before the iPhone, with enthusiastic crowds turning out nationwide to watch its train car pass on the way from the site of its torturous manufacturing process at Corning

Palomar Observatory

LOCATION: Palomar Mountain, California
WEBSITE: www.astro.caltech.edu/palomar
VISITORS WELCOME:

9 A.M. to 3 P.M. PST daily; 9 A.M. to 4 P.M. PDT daily

TOURS: 11 A.M., 1 P.M., and 2:30 P.M.
 Saturday and Sunday, April–October

TELESCOPES:

- 200-inch Hale Telescope
- 60-inch Telescope
- 48-inch Samuel Oschin Telescope

Glass Works in New York to Southern California. There, it underwent a lengthy polishing at the California Institute of Technology in Pasadena before being inched up the mountain.

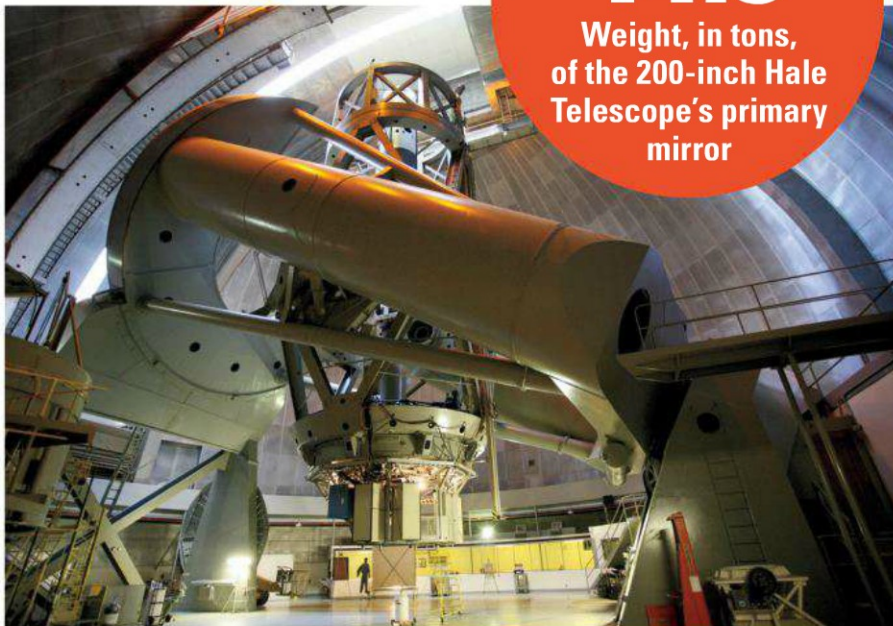
Unfortunately, public outreach support at Palomar is not nearly as massive as the wonderful facilities, which include a small but attractive visitor center. Most days, visitors are left to conduct a self-guided walking tour, which can include a fairly steep climb up stairs to reach the glassed-in visitor gallery for the 200-inch. Weekend guided tours and gift shop access are due to resume in April 2012, augmented by some newly donated detailed models of the 200-inch built by a longtime staff engineer who recently passed away.

It's also worthwhile for historic purposes to visit the exterior of the 48-inch Samuel Oschin Telescope, which has been used to take hundreds of thousands of wide-field exposures of the night sky through a Schmidt camera, including the historic National Geographic-funded Palomar Observatory Sky Survey from 1949 to 1958.

Driving from Palomar to Mount Wilson through the urban sprawl of Orange County and downtown Los Angeles, it's hard to believe anyone could think it would be a prime spot for a major astronomical observatory. However, the San Gabriel Mountains looked down on a much different and darker valley when this legendary observatory was painstakingly developed in the early 1900s.

2009

The year Mount Wilson came under threat of a California wildfire



14.5

Weight, in tons, of the 200-inch Hale Telescope's primary mirror

THE 200-INCH HALE TELESCOPE ranked as the largest in the world for more than a quarter-century after its completion in 1949. SCOTT KARDEL (PALOMAR OBSERVATORY)

Mount Wilson's centerpiece is the undeniably Industrial Age-looking 100-inch Hooker Telescope. Try to get a look inside at its wine bottle-glass mirror, used so memorably by a pipe-smoking Edwin Hubble to first map out the velocity slope of the expanding universe in the 1920s. The observatory's deepest roots actually lie in solar science, where a tall wood and metal tower constructed by Hale has produced an unmatched multi-decadal record of sunspots and other major features, drawn daily by hand.

Today, the only world-class science on the mountain is done by the Center for High Angular Resolution Astronomy (CHARA) Array, six small telescopes operated by Georgia State University. Distributed in the shape of a "Y" over a

maximum length of some 1,000 feet (300m), these individual 1-meter telescopes link together with an accuracy of one-millionth of an inch to produce what operators claim to be the highest-resolution visible and infrared images from any facility in the world.

The ultimate visitor experience at the observatory is a private viewing party with the Mount Wilson 60-inch Telescope, used famously by Harlow Shapley to deduce that the Sun is far from the center of the Milky Way. Gates through the Angeles National Forest to the observatory are open from April through November, and the weekend afternoon tours now include access to the floor of the Hooker Telescope and the 150-foot solar tower. ☼

Mount Wilson Observatory

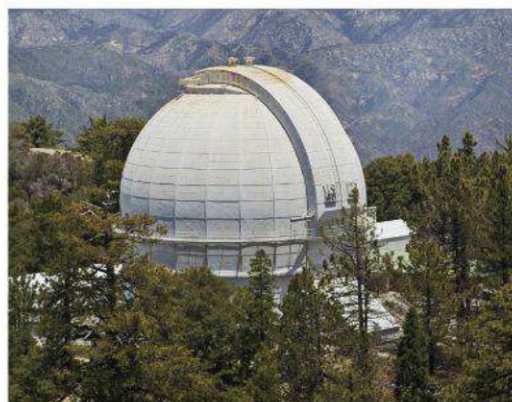
LOCATION: Mount Wilson, California
WEBSITE: www.mtwilson.edu
VISITORS WELCOME:

10 A.M. to 4 P.M. daily
 April–November

TOURS: 1 P.M. Saturday and Sunday, April–November

TELESCOPES:

- 100-inch Hooker Telescope
- 60-inch Telescope
- 150-foot Solar Telescope
- 60-foot Solar Telescope
- Infrared Spatial Interferometer
- CHARA Array



THE 100-INCH HOOKER TELESCOPE on Mount Wilson, in the San Gabriel Mountains outside Los Angeles, helped Edwin Hubble map out the expanding cosmos. DAVE JURASEVICH, MOUNT WILSON OBSERVATORY

Lick Observatory

LOCATION: Mount Hamilton, California

WEBSITE: www.ucolick.org

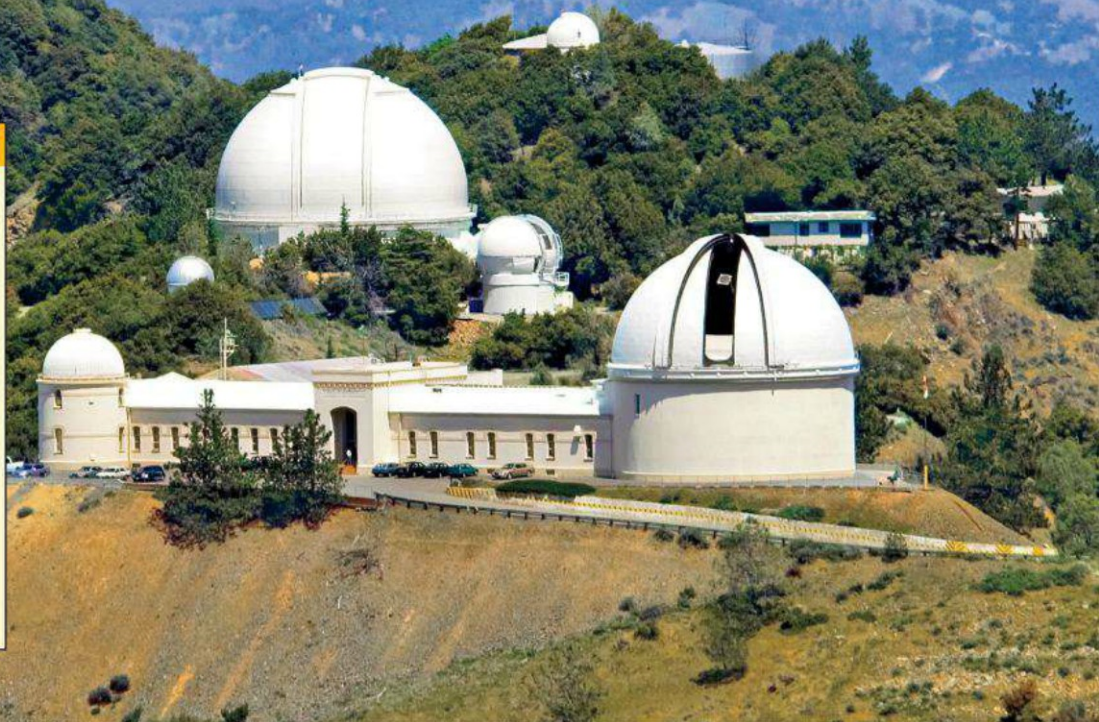
VISITORS WELCOME:

12 P.M. TO 5 P.M. Thursday–Sunday
(Visitor Center); 10 A.M. to 5 P.M. daily
(Shane Gallery)

TOURS: Every half-hour starting at
1 P.M. Thursday and Friday,
12:30 P.M. Saturday and Sunday

TELESCOPES:

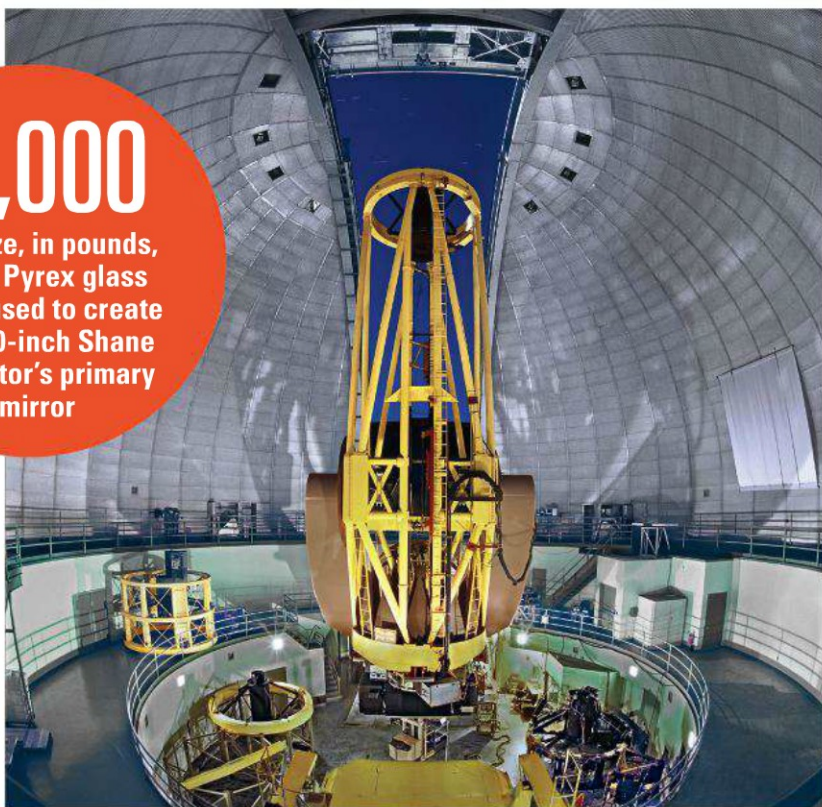
- C. Donald Shane 120-inch Reflector
- 2.4-meter Automated Planet Finder
- Nickel 1-meter Reflector
- 36-inch Great Lick Refractor
- 36-inch Crossley Reflector
- 20-inch Carnegie Double Astrograph



LICK OBSERVATORY resides on Mount Hamilton east of San Jose, California. Here, the observatory's 36-inch refractor (foreground) views the Sun while the 120-inch Shane Reflector and other scopes await nightfall. LAURIE HATCH

10,000

The size, in pounds,
of the Pyrex glass
blank used to create
the 120-inch Shane
Reflector's primary
mirror



THE 120-INCH SHANE REFLECTOR stood as the world's second-largest optical telescope for nearly 15 years after its completion in 1959. LAURIE HATCH

Northwest nights

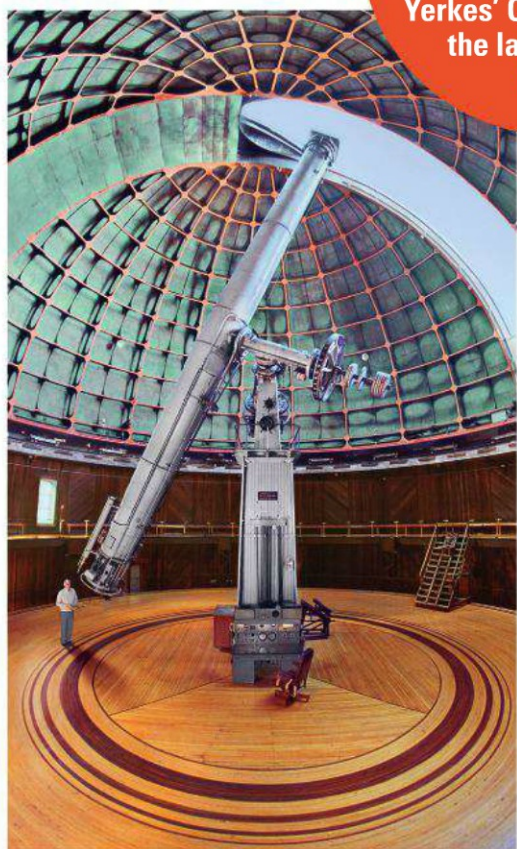
Mount Hamilton, California

While the observatories of Southern California were forming with funding from the thick coffers of the Rockefeller and Carnegie foundations, the greatest observatory of the northwestern U.S. was largely the beneficiary of the next best thing: one extremely wealthy individual.

Lick Observatory on Mount Hamilton, east of San Jose, California, owes its origins in the late 19th century to the grandiose desire of aging real-estate magnate James Lick to memorialize himself in a grand manner. (Lick's first and second choices were humongous statues of himself and his parents on the Pacific coastline and a gigantic pyramid in downtown San Francisco, respectively; luckily for astronomy and society at large, he settled on a grand observatory on a peak visible from his rural home, although he

40

The aperture, in inches, of Yerkes' Clark Refractor, the largest in the world

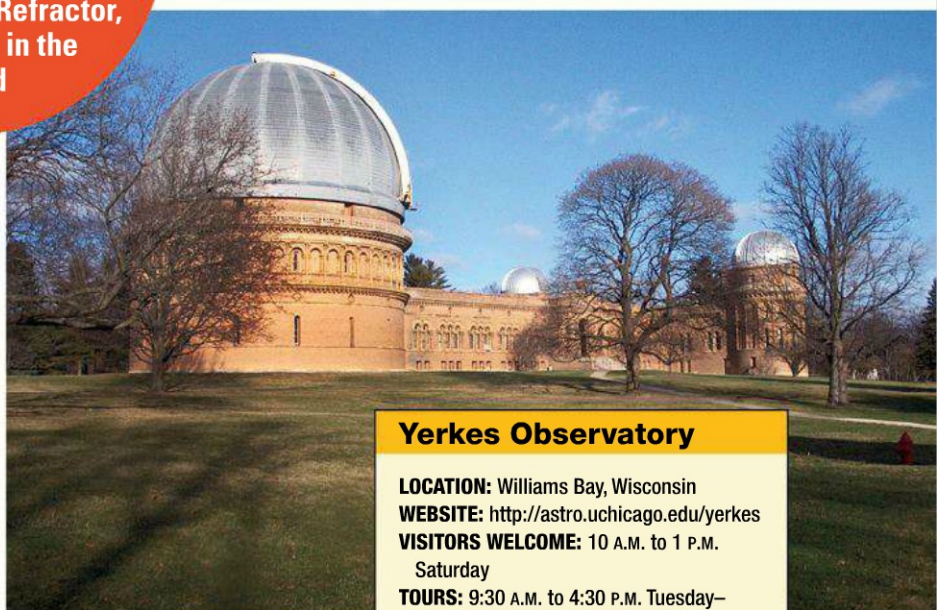


THE 36-INCH LICK REFRACTOR was the largest in the world when it saw first light in 1888; it remains third in the refractor hierarchy even today. The telescope resides on an equatorial mount inside a large dome necessitated by its enormous focal length of 57.7 feet (17.6 meters). LAURIE HATCH

did make sure his final resting place was under the main telescope's pier.)

Lick Observatory's most famous instruments are its 36-inch Great Lick Refractor from 1888 and the C. Donald Shane 120-inch Reflector, the second-largest in the world for the first 15 years of its 50-year-plus lifetime. The Shane has been a workhorse for famous exoplanet-hunters Geoff Marcy, Debra Fischer, and Paul Butler, who have arguably done more than any research group in promoting general knowledge about the more than 700 planets detected to date around other stars. The Shane telescope's primary mirror was formed from a 10,000-pound (4,500 kilograms) Pyrex glass blank produced as a prototype for the 200-inch Hale Telescope on Palomar Mountain.

Guided tours of Lick are available starting at the visitor center every half-hour in the afternoons during its regular Thursday through Sunday hours, along with self-guided tours of the Shane and its viewing gallery. When major sky events occur, the observatory often connects with other Bay Area science venues such as the Exploratorium for outreach activities. ☼



Yerkes Observatory

LOCATION: Williams Bay, Wisconsin
WEBSITE: <http://astro.uchicago.edu/yerkes>
VISITORS WELCOME: 10 A.M. to 1 P.M. Saturday

TOURS: 9:30 A.M. to 4:30 P.M. Tuesday–Friday (reservations required); 10 A.M., 11 A.M., and noon Saturday

TELESCOPES:

- 41-inch reflector
- 40-inch Clark Refractor
- 24-inch reflector

YERKES OBSERVATORY in Wisconsin features the largest refractor on Earth — a 40-inch behemoth housed inside the big dome at left. KYLE CUDWORTH (UNIVERSITY OF CHICAGO)

Where it all began

Williams Bay, Wisconsin

If avid tourists haven't reached their limit by now, there is one more stop that they must check off their list in order to cover the full historical span of major American observatories.

It's a short drive from Milwaukee, Wisconsin, to the bucolic shores of Lake Geneva, home to Yerkes Observatory and its venerable 40-inch Clark Refractor (the largest in the world), whose slender profile remains a potent symbol of the power of astronomy to capture the public imagination. It is also the project that convinced the ever-restless George Ellery Hale that he had the skills needed to accomplish projects on the scale of his subsequent massive contributions to Mount Wilson and Palomar Mountain (see pages 40 and 41).

Observatory operators recently added personalized tours for family-sized groups to the larger-group tours (all by advance reservation). A viewing party with a 24-inch telescope is the most memorable experience offered today at Yerkes, which appears to have a bright future as a regional education center after a few years of uncertainty and rumors of closure or repurposing. ☼

As exemplified by many of the repeated names throughout this section, a pictorial diagram of all these U.S. mainland observatories would show as many connections and reconnections as the nervous system of the human body. Any of them is a great place to spark or renew a love for the wonders of the universe and the shared human dedication that allows us to explore them with such amazing fidelity. ☼



High and dry

Most of the Southern Hemisphere's premier astronomical sites lie in the Atacama, Earth's driest desert.

By José Maza



The Atacama Desert in northern Chile has become the site of choice for many big astronomical projects. The Very Large Telescope, as its name might suggest, ranks among the most prodigious observatories in the world. Moreover, this region is one of the driest on Earth, allowing for exceptional sky conditions. Cerro Paranal, home to this telescope, claims 330 clear nights per year. The prevailing wind blows from the northwest over the Pacific Ocean for thousands of miles, creating few disruptions in airflow, and the Chilean Coast Range lies between the desert and the ocean. That blocks the moisture, so the quality of images and astronomical data obtained here is fantastic.

José Maza is a professor of astronomy at the University of Chile in Santiago. In 1999, he won Chile's National Medal for Exact Sciences.

Earliest visit

In the summer of 1958, University of Chile National Observatory Director Federico Rutllant visited the United States with two goals in mind: to attend science conferences and to seek help promoting Chilean astronomy. He traveled to Yerkes Observatory in Williams Bay, Wisconsin, and suggested to its director, Gerard Kuiper, that Chile was an excellent choice on which to establish a southern observatory.

CHILE ASTRONOMY IN

THE MILKY WAY arches above Cerro Paranal and the four enclosures of the Very Large Telescope. The photographer took this panorama during the total lunar eclipse of December 21, 2010 (the ruddy Moon lies above the third scope from the right). ESO/Y. BELETSKY

By coincidence, American astronomers were looking for a location to establish a southern field station, most likely in South Africa or Australia. Rutlant proposed Chile as a better alternative, with the benefit that it was closer to the United States. Further sweetening the deal, the University of Chile offered to collaborate by locating a good mountain and helping in the construction of a 40-inch reflector.

In the spring of 1959, Jürgen Stock of the University of Chicago and the University of Texas arrived in Chile on Kuiper's recommendation to explore the

area. Two astronomers from the University of Chile joined him: Hugo Moreno and Carlos Torres. Stock's reports of sky clarity were so enthusiastic that it was clear the area could prove useful for a major astronomical observatory. The next year, the Association of Universities for Research in Astronomy (AURA) took over administration of the project, with the universities of Chile, Chicago, and Texas on the board of directors.

Stock had experience searching for observatory sites, and he quickly fell in love with Cerro Tololo in the Elqui Valley,

some 400 miles (640 kilometers) north of Santiago. This excellent site boasts upward of 300 clear nights per year at 7,200 feet (2,200 meters) above sea level. The name of the mountain supposedly comes from a steep drop on its north face, which the ancient inhabitants called *tololo*, or "in front of the abyss."

By 1962, the team had come to a decision. The new facility, a collaborative effort between North and South American astronomers, received the name Cerro Tololo Inter-American Observatory (CTIO).



1974

When the 4-meter Victor M. Blanco Telescope saw first light

Cerro Tololo Inter-American Observatory

LOCATION: Cerro Tololo, Chile

WEBSITE: www.ctio.noao.edu

TOURS: 9 A.M. and 1 P.M. every Saturday during winter and summer (reservations required)

TELESCOPES:

- 4-meter Victor M. Blanco Telescope
- SMARTS 1.5-meter Telescope
- SMARTS 1.3-meter Telescope
- SMARTS 0.9-meter Telescope

CERRO TOLOLO INTER-AMERICAN OBSERVATORY rests atop a 7,200-foot-tall (2,200 meters) mountain in the foothills of the Andes in northern Chile. NOAO/AURA/NSF

Cerro Tololo

Stock became CTIO's first director in 1963, and construction on the site soon began. He had already hauled a 0.41-meter telescope to the summit during site testing, so the first buildings to go up included a primitive cover for it. This was no easy task in the early 1960s, when trips to the peak were possible only on mule or horseback, and traveling to the nearest town (the coastal city of Los Placeres) took at least 2 days.

By 1967, CTIO had two 0.41-meter telescopes in service. A 1.5-meter scope was also ready just in time for the

November 7 inauguration by Chilean President Frei Montalva, among others. The event saw the official announcement of CTIO's plans to install a 4-meter telescope. That instrument guaranteed the Chilean facility's status as a major observatory for years to come.

AURA had trouble finding local contractors to build CTIO's facilities, so the association of astronomers used its own workers and equipment for the 4-meter's housing (like most of the telescopes before and after it). When science observations began in January 1976, it was the largest telescope in the Southern Hemisphere.

Eventually named after CTIO director and Puerto Rican astronomer Victor M. Blanco, the 4-meter scope remains one of the most scientifically useful astronomical instruments south of the equator. It has gathered data that led to many significant astronomical advances, including the discovery of distant supernovae that in 1998 led two American groups — the Supernova Cosmology Project and the High-*z* Supernova Search — to announce that the universe is expanding at an accelerating rate. This work won the 2011 Nobel Prize in physics for researchers Saul Perlmutter, Brian Schmidt, and Adam Riess. ☼

Tololo

A native word originally meaning "in front of the abyss"



SUPERNOVA 1987A (the bright point right of center) was the closest exploding star in nearly 400 years — and visible best from the Southern Hemisphere. MARCELO BASS, CTIO/NOAO/AURA/NSF



THE 4-METER VICTOR M. BLANCO TELESCOPE rises 13 stories above the observing platform on Cerro Tololo. It was the first large scope in the Southern Hemisphere. T. ABBOTT AND NOAO/AURA/NSF



Chile serves up big scopes



THE SUMMIT OF CERRO PACHÓN, located 15 miles (24 kilometers) southeast of Cerro Tololo, boasts two instruments: the 8.1-meter Gemini South Telescope (foreground) and the 4.1-meter Southern Astrophysical Research Telescope. GEMINI OBSERVATORY

Cerro Pachón Observatory

LOCATION: Cerro Pachón, Chile

WEBSITES: www.gemini.edu/public/pachon.html
www.soartlescope.org

TOURS: by appointment only

TELESCOPES:

- 8.1-meter Gemini South Telescope
- 4.1-meter Southern Astrophysical Research Telescope

La Silla Observatory

LOCATION: Cerro La Silla, Chile

WEBSITE:

www.eso.org/public/teles-instr/lasilla

TOURS: 1:30 P.M. Saturdays
(registration required)

TELESCOPES:

- 3.6-meter ESO Telescope
- 3.58-meter New Technology Telescope
- 1.54-meter Danish Telescope
- Swiss 1.2-meter Leonhard Euler Telescope

Cerro La Silla

Once European astronomers saw how successful CTIO was, they followed AURA in establishing an observatory in Chile's Atacama Desert. The five countries that then

made up the European Southern Observatory (ESO) looked for a suitable site near CTIO and found an interesting ridge some 80 miles (130km) north called Cerro La Silla (originally called Cerro Las Viscachas;

ACTIVE OPTICS and a then-novel enclosure highlight the New Technology Telescope. ESO

Cerro Pachón

9

The maximum number of instruments the SOAR Telescope can use

In the mid 1990s, AURA began a new project: the Gemini Observatory, which would comprise twin 8.1-meter telescopes. One would sit in the Northern Hemisphere on Hawaii's Mauna Kea (see page 18) and the other in the Southern Hemisphere on Chile's Cerro Pachón. AURA's property already included this mountain, located some

6 miles (10km) southeast of CTIO and rising 9,000 feet (2,700m) above sea level, roughly 1,800 feet (550m) higher than CTIO.

The difference in elevation makes it a better location for the Gemini telescope, which observes in the infrared region in addition to the optical. Since 2001, when the Gemini South Telescope saw first

light, the twin scopes have captured almost the entire sky, except for areas near the celestial poles.

Cerro Pachón also became the site for the 4.1-meter Southern Astrophysical Research (SOAR) Telescope that saw first light in April 2004. An international consortium (including Chile and CTIO) built and runs this instrument. ☼



STARS ARE BORN at the tips of dusty pillars in this section of the Lagoon Nebula (M8). Astronomers took this false-color image with the Gemini South Telescope. GEMINI OBSERVATORY



GALAXIES NGC 5426 AND 5427 tango in each other's gravitational embrace in this Gemini South image. GEMINI OBSERVATORY

the new name means “the saddle”). In 1964, ESO bought 242 square miles (627 square km) of land around the 7,900-foot-high (2,400m) mountain and began work on La Silla Observatory.

After years of construction, guests from various governments and AURA saw the observatory inaugurated in March 1969. It quickly gained

a variety of scopes, including a 1.0-meter, 1.5-meter, a 1.2-meter Schmidt, and a 3.6-meter instrument, all owned and operated by ESO.

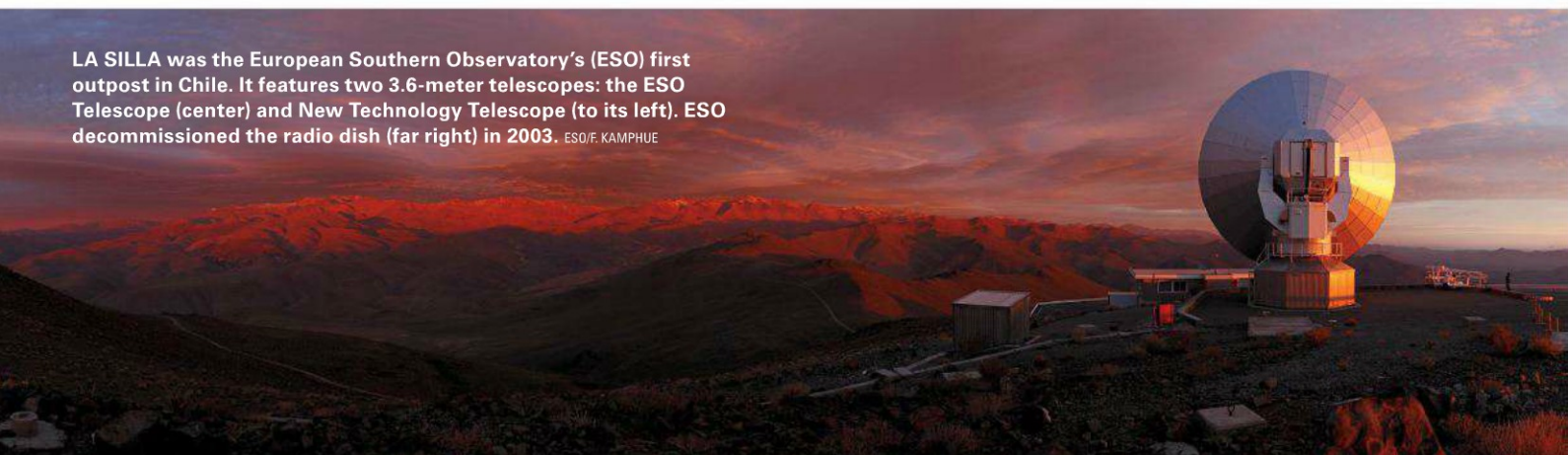
This last, which saw first light in November 1976, was a superb instrument, capable of direct photography, infrared photometry, and all kinds of spectroscopy. For years, it was the direct competitor of

CTIO's 4-meter Blanco Telescope, and it remains a viable instrument even today. La Silla Observatory also hosts numerous “national telescopes” owned and operated by one of ESO's 14 (plus one pending) member states.

When ESO began planning its era of 8-meter telescopes, it started testing sites near La Silla and also one far to the

north named Cerro Paranal. The seeing conditions at Paranal, 400 miles (644km) from La Silla, were so much better that ESO decided to create a new observatory there. Few telescopes still operate at La Silla, but those include ESO's 3.6-meter New Technology Telescope, their 1.54-meter Danish Telescope, and the 3.6-meter ESO scope. ☼

LA SILLA was the European Southern Observatory's (ESO) first outpost in Chile. It features two 3.6-meter telescopes: the ESO Telescope (center) and New Technology Telescope (to its left). ESO decommissioned the radio dish (far right) in 2003. ESO/E. KAMPHUE





SUNSET HERALDS another clear night on Cerro Paranal, where the Very Large Telescope's four instruments await nightfall. ESO/F. KAMPHUES

Cerro Paranal Observatory

Surprisingly close to the Pacific Ocean — just 8 miles (13km) inland — Paranal Observatory rises 8,600 feet (2,600m) above sea level. Some consider it the best observatory in the world with its claim of 330 clear nights a year. It's also the site of the Very Large Telescope (VLT), the no-nonsense name of the flagship for European ground-based astronomy.

The VLT is made up of four 8.2-meter Unit Telescopes (UT), the first of which began operations in 1998. Named Antu,

Kueyen, Melipal, and Yepun (respectively, the Sun, the Moon, the Southern Cross, and Venus in the Mapuche language of central Chile), the UTs can observe individually or combine to effectively form a 16-meter instrument known as the Very Large Telescope Interferometer (VLTI). Four Auxiliary Telescopes (AT) of 1.8 meters each also complement the VLTI, working as a separate interferometer to free up the main scopes, allowing for improved imaging and complete year-round nighttime use.

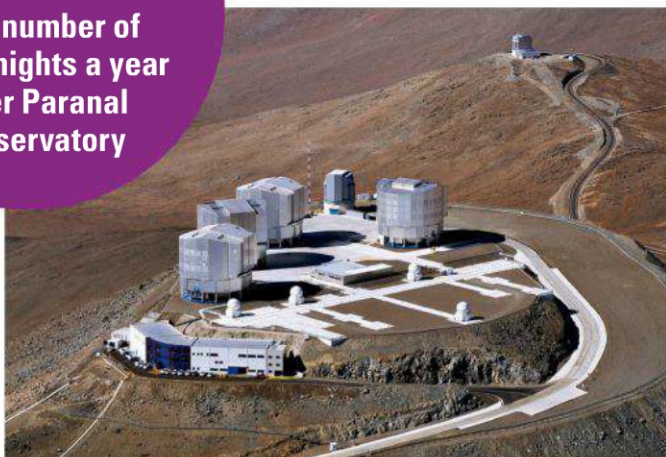
Not satisfied with its VLT, Paranal Observatory recently added two new telescopes: the Visible and Infrared Survey

Telescope for Astronomy (VISTA) and the VLT Survey Telescope (VST). The former began operations in 2009, and at 4.1 meters is the world's largest survey telescope; effectively, it's a 67-megapixel infrared camera with a 13,000mm focal length f/3.25 mirror lens. Each exposure covers more than half a square degree of sky.

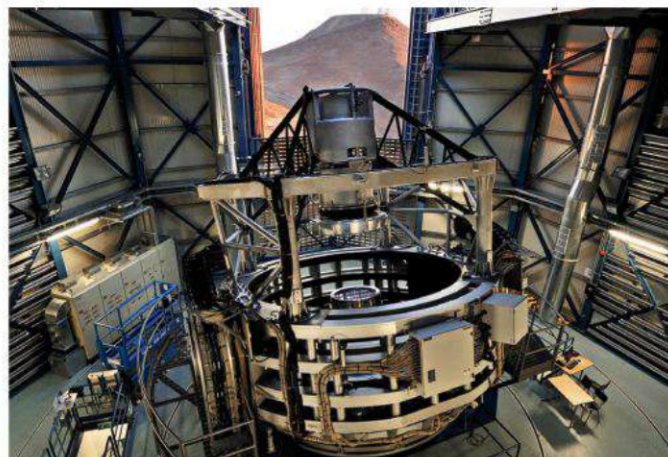
The VST started up in 2011 and consists of a 2.61-meter modified Ritchey-Chrétien reflector equipped with a 268-megapixel CCD camera. It covers a 1° by 1° patch of sky (an area four times larger than the Full Moon), and is the world's largest scope meant for visible-light sky surveys. ☼

330

The number of clear nights a year over Paranal Observatory



THE FOUR BIG "DOMES" of the Very Large Telescope (VLT) frame the VLT Survey Telescope; the adjoining peak houses the Visible and Infrared Survey Telescope for Astronomy. ESO/G. HÜDEPOHL



WITH A 4.1-METER MIRROR, the Visible and Infrared Survey Telescope for Astronomy is the world's largest survey instrument. It maps the sky at near-infrared wavelengths. ESO/G. HÜDEPOHL

Paranal Observatory

LOCATION: Cerro Paranal, Chile

WEBSITE: www.eso.org/public/teles-instr

TOURS: 9:30 A.M. and 1:30 P.M.

Saturdays (reservations required)

TELESCOPES:

- Four 8.2-meter Unit Telescopes for the Very Large Telescope
- Four 1.8-meter Auxiliary Telescopes for the Very Large Telescope Interferometer
- 4.1-meter Visible and Infrared Survey Telescope for Astronomy
- 2.61-meter VLT Survey Telescope

430,000

The mass, in kilograms, of each VLT Unit Telescope



THE SKY ROTATES above the Very Large Telescope. Stars that form lines lie on the celestial equator while stars to the south (left) and north (right) make curves. ESO/STÉPHANE GUISARD



BARRED SPIRAL GALAXY NGC 6872 in Pavo the Peacock interacts with its smaller neighbor, IC 4970. Astronomers captured the pair with one of the 8.2-meter Unit Telescopes of the Very Large Telescope. ESO



STAR-FORMING REGION MONOCEROS R2 weaves a web of nebosity in a near-infrared image taken by the Visible and Infrared Survey Telescope for Astronomy. ESO/J. EMERSON/VISTA



GLOBULAR CLUSTER OMEGA CENTAURI shows up in all its glory through the VLT Survey Telescope. The scope's wide field captured the whole cluster — some 300,000 stars. ESO/INAF-VST/OMEGACAM

Pure fused silica

What the Irénée du Pont Telescope's primary mirror is made of

Las Campanas Observatory

LOCATION: Cerro Las Campanas, Chile

WEBSITE: www.lco.cl

TOURS: Saturdays by appointment only

TELESCOPES:

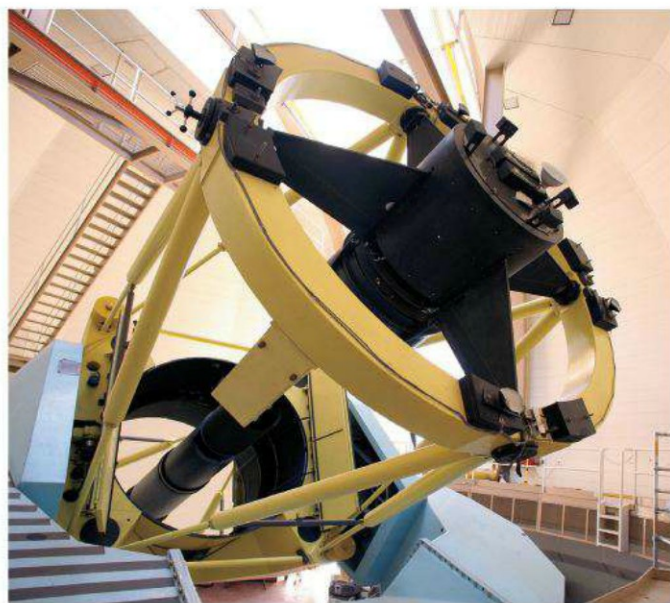
- Two 6.5-meter Magellan Telescopes
- 2.5-meter Irénée du Pont Telescope
- 1-meter Henrietta Swope Telescope

Las Campanas

Similarly to AURA and ESO, in the 1960s the Carnegie Institution of Washington (CIW) was looking for a site in the Southern Hemisphere on which to build a large telescope. Having operated California's Mount Wilson and Palomar Mountain observatories (see page 30) for decades, the institution was ready for a southern view. Initially seeking to collaborate with AURA, John Irwin of the CIW worked with Jürgen Stock to site test cerros Tololo and Morado. Finally, by decade's end, Carnegie decided to establish its own observatory atop Cerro Las Campanas ("the bells").

By 1971, CIW's first telescope was ready: the 1-meter Henrietta Swope Telescope, named after a former CIW astronomer. The 2.5-meter Irénée du Pont Telescope came next, the namesake of the DuPont company business mogul, and it began operations in 1977. These both fell far short of the original goal of 5 meters, but the du Pont is an amazing photographic telescope with a design that gives it a field of view up to 2.1° across. American astronomer Allan Sandage used the Irénée du Pont Telescope to capture some of the best images of southern galaxies, and the scope features various instruments built by Steve Shetman, one of the world's most famous astronomical instrument makers.

LAS CAMPANAS features the twin 6.5-meter Magellan Telescopes (right), the 2.5-meter Irénée du Pont Telescope (big dome at left), and the 1-meter Henrietta Swope Telescope (far left).



THE IRÉNÉE DU PONT TELESCOPE has a 2.5-meter mirror and excels as a photographic instrument, resolving exquisite detail in a field of view up to 2.1° across. LAS CAMPANAS OBSERVATORY

Future projects



THE 6.5-METER PRIMARY of the Walter Baade Telescope sits inside this mirror cell. The Baade scope was the first of the twin Magellan instruments completed. LAS CAMPANAS OBSERVATORY



THE TWIN MAGELLAN TELESCOPES bathe in late-afternoon light. The pair sits some 200 feet (60 meters) apart on the isolated summit of Cerro Manqui. LAS CAMPANAS OBSERVATORY

In the 1990s, CIW teamed up with four American universities to put two large instruments at Las Campanas: the twin Magellan Telescopes. The two 6.5-meter scopes, named after astronomer Walter Baade and philanthropist Landon T. Clay, are today the most productive telescopes at the observatory. Both feature a special optical design — a Gregorian configuration instead of the classic Cassegrain — that allows for larger fields of view. Unfortunately, while the dream of a large CIW scope in the south had finally come true, it was after the VLT and Gemini South began operations, slightly diminishing the Magellans' influence. ☛

The success of observatories in Chile inspired many projects due to come online during the next decade. The internationally run Atacama Large Millimeter/submillimeter Array (ALMA) actually began scientific observations in late 2011. When complete in 2013, 66 radio antennas will observe from the Chajnantor Plateau of the Atacama Desert some 16,500 feet (5,000m) above sea level.

AURA's Large Synoptic Survey Telescope will be an 8.4-meter scope with a unique optical configuration and a huge digital camera of about 3,200 megapixels. Each of its exposures will cover an area some 49 times the size of the Full Moon. If all goes according to plan, it'll perform weekly surveys in multiple colors of the entire sky visible from Cerro Pachón, near the Gemini South and SOAR telescopes, from a ridge 8,800 feet (2,700m) high. It should gather a total of 50 petabytes during a decade of observations. First light should occur in a few years, with full science operations starting at the end of the 2010s.

CIW also has embarked on another ambitious project — the Giant Magellan Telescope (GMT), consisting of seven 8.4-meter telescopes in a daisy-like configuration. With a collecting area 24.5 meters in diameter, some

12 times bigger than the Baade or Clay scopes, and 10 times the resolving power of the Hubble Space

Telescope, the GMT's mirrors will gather more light than any telescope in history. Las Campanas Observatory hopes to complete it by 2019.

At the ALMA site, on a little mountain 1,500 feet (450m) above the Chajnantor Plateau, the Cornell Caltech Atacama Telescope (CCAT) should see first light in 2015. Stretching 25 meters in diameter, this behemoth will survey millimeter and submillimeter light in unprecedented detail. Among other things, CCAT will shed light on galactic and stellar evolution, interstellar gas, planetary formation, and distant solar system objects.

But the most ambitious Chilean project under consideration is ESO's European Extremely Large Telescope (E-ELT), a 40-meter telescope consisting of almost 800 hexagonal mirrors. This project doesn't come cheap: Its price tag tops \$1 billion. Still, astronomers consider it worth the investment because it will become the most powerful optical telescope in the world upon its completion in the early 2020s. In 2010, ESO chose Cerro Armazones, only 20 miles (32km) east of Cerro Paranal, as the future location of the E-ELT. If successful, it should be able to locate Earth-like exoplanets within their stars' habitable zones and probe the unsolved nature of dark matter and dark energy.

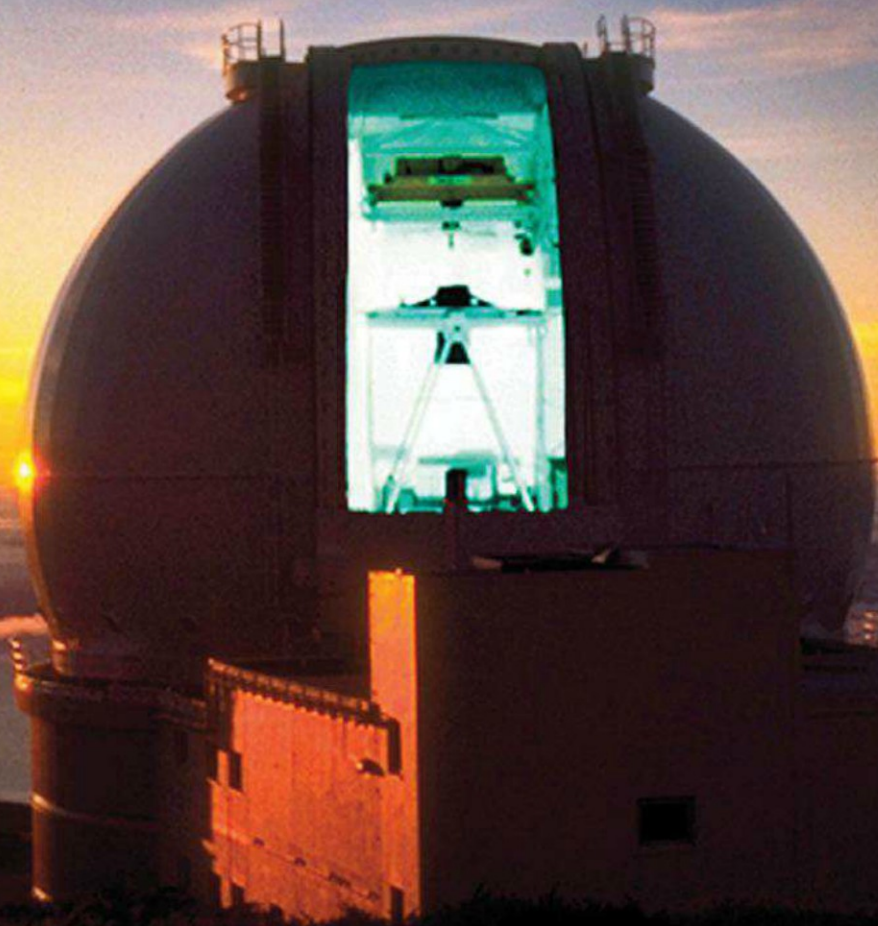
If the past is any indication, these projects will all contribute greatly to astronomy, bringing glory not just to themselves, but also to the Chilean skies that made it all possible. ☛

40

The planned aperture, in meters, of the European Extremely Large Telescope

CANARY ISLANDS SCOPES

Europe's eyes on the





The world's largest optical telescope joins many other superb astronomical instruments on an island off of Africa's northwestern coast.

By Chris Benn, Javier Méndez,
and Marc Balcells

northern sky

The Canary Islands

The Canary Islands, off the northwest coast of Africa, have long been a popular tourist destination, enticing visitors with their mild weather and historical attractions. But the northwest-most island in the archipelago, named La Palma, has its own astronomical allures.

At the 7,900-foot (2,400 meters) summit of one of its peaks, high above the clouds, sits one of the best observing sites on Earth. Many of Europe's most powerful telescopes take advantage of these skies, including the largest single-aperture opti-

cal telescope in the world. As a result, some of the most important space discoveries happened with these instruments.

La Isla Bonita

The locals call La Palma *La Isla Bonita* — the beautiful island. It's the greenest of the seven Sun-drenched Canary Islands, thanks to the plentiful supply of water provided by the high, steep slopes. Palm trees, primeval laurel forest, and pines all find their home here, as do plantations of diverse crops from bananas to tobacco.

Like the nearby islands, La Palma sees volcanic activity. The original peak in the northern part of the island collapsed long ago, leaving behind the Caldera de Taburiente — a steep-walled crater 5 miles (8 kilometers) across and 0.93 mile (1.5km)

THE WILLIAM HERSCHEL
TELESCOPE peers out from
a sunlit dome on a late
afternoon. The Milky Way
rides overhead in this
composite image.

NIK SZYMANEK AND IAN KING/ING

Chris Benn is head of astronomy at the
Isaac Newton Group of Telescopes (ING).

Javier Méndez is public relations officer
at the *ING*. **Marc Balcells** is director of
the *ING*.

CANARY ISLANDS SCOPES

Liverpool Telescope
SIZE: 2.0 meters

Jacobus Kapteyn Telescope (retired)
SIZE: 1.0 meter

Swedish Solar Telescope
SIZE: 1.0 meter

Dutch Open Telescope
SIZE: 0.45 meter

Nordic Optical Telescope
SIZE: 2.56 meters

Isaac Newton Telescope
SIZE: 2.54 meters

William Herschel Telescope
SIZE: 4.2 meters

MAGIC I and II
SIZE: 17 meters each

THE ROQUE DE LOS MUCHACHOS OBSERVATORY stretches out along the rim of the Caldera de Taburiente, some 7,900 feet (2,400 meters) above sea level on La Palma in the Canary Islands. GIOVANNI TESSICINI (TNG)

deep. The caldera and the northern half of the island are no longer volcanically active, but the southern half has seen many eruptions, most recently in 1971.

Going a little further back, during the Spanish conquest of the 15th century, the local inhabitants of the Canary Islands were the *Guanches*. How and when they arrived is still unknown, and their culture disappeared after the Spanish conquest. But they left behind a wealth of enigmatic rock carvings and distinctive place names (Tigalate, Tenagua, Tijarafe), and *Guanche* genes live on in the blond hair of many Canary Islanders.

Over the next 200 years, La Palma's abundant water and its role as a trading post on the way to the New World made it one of the Canaries' wealthier islands,

and a target for pirates. The seafront fort kept at bay the likes of Sir Francis Drake, who attacked unsuccessfully in 1585.

One feature La Palma lacks is golden beaches, but this has turned out to be a blessing for astronomers. The hordes of Northern European tourists who flock to the sunny resorts of Tenerife and Gran Canaria to the east have largely shunned the black volcanic sands of La Palma. As a result, there are no brightly lit resorts on the island, and the skies of La Palma are as dark as those of Chile or Hawaii.

Open for business

In the late 1960s, British astronomers were hatching plans for a Northern Hemisphere observatory. They were helping build the 3.9-meter Anglo-Australian

Telescope in the Southern Hemisphere and wanted a similar telescope in the north. At the time, the United Kingdom's largest telescope was the 2.54-meter Isaac Newton Telescope (INT) at Herstmonceux Castle in Sussex, but the English weather often made observing difficult. The scope deserved and needed a better site, and the astronomers were looking to sunnier climes in the Mediterranean area, various Atlantic islands, and Hawaii.

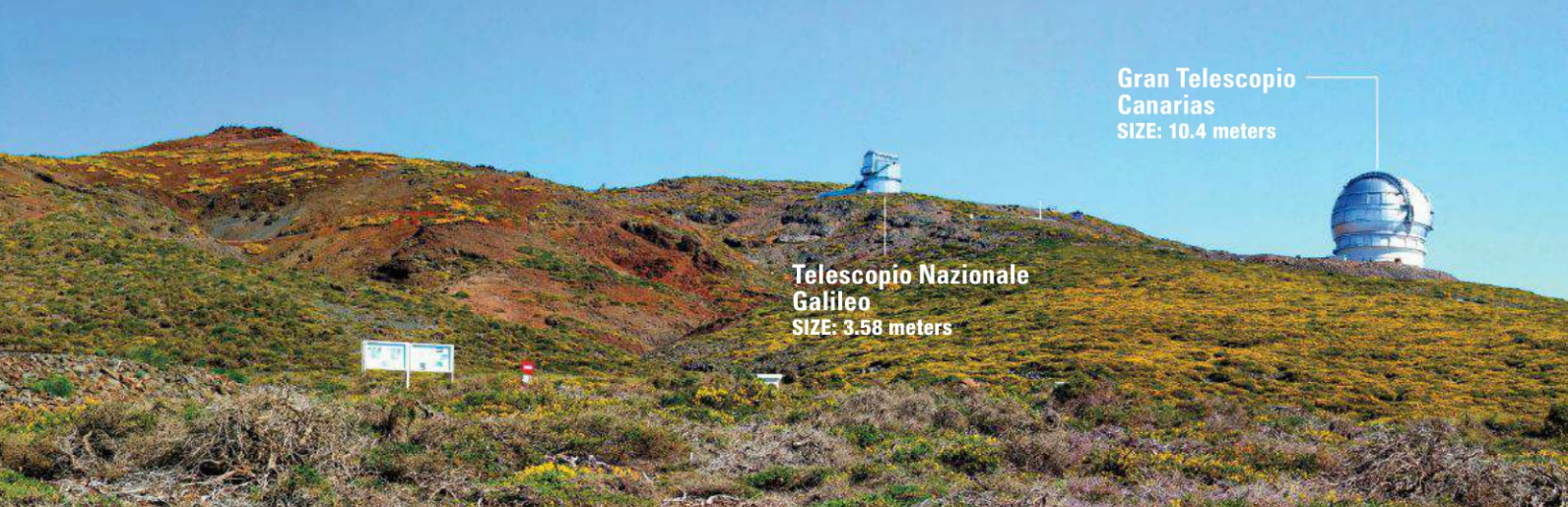
La Palma emerged as a possible site in 1971 when two astronomers from the Royal Greenwich Observatory stopped at the island and visited the summit, on the rim of the Caldera de Taburiente. The prevailing wind blows from the northwest and passes only over the smooth northern flank of the island before reaching the rim of the caldera, which bodes well for steady airflow and good seeing.

The next year, mules ferried supplies and equipment to La Palma's summit, and site testing began. By 1975, the results were in, and four locations had made the cut: Hawaii, Madeira (far southwest of Portugal), and the Canary Islands of Tenerife and La Palma. Hawaii and La Palma eventually came out on top, with little to distinguish between them astronomically. La Palma, however, is much easier for European astronomers to reach.

At about the same time, thanks to the enthusiastic Spanish astronomer Francisco Sánchez, Spain's government began to understand the importance of creating an international observatory on the Canaries. In 1979, Spain, Denmark, Sweden, and the U.K. signed an agreement: Spain would provide the observatory infrastructure, and in exchange its astronomers would get 20 percent of the observing time on all telescopes located there. The foundations of La Palma's



THE RUGGED CONTOURS of the fog-filled 5-mile-wide (8 kilometers) Caldera de Taburiente National Park stand out in this view. INSTITUTO DE ASTROFÍSICA DE CANARIAS



**Gran Telescopio
Canarias**
SIZE: 10.4 meters

**Telescopio Nazionale
Galileo**
SIZE: 3.58 meters

international observatory were in place; it would be called the Observatorio del Roque de los Muchachos (ORM) after a nearby rocky landmark (literally named “the rock of the boys”).

These international agreements, recently extended until 2022, establish a flexible scheme to allow scientific organizations to deploy their telescopes on a site with all the required infrastructure in place: access roads, living quarters, a water supply, electricity, and communications networks. Today, 13 telescopes operate on the ORM under this agreement.

The first scopes

The first telescope on La Palma was a Swedish 24-inch, commissioned in 1982. The next would be the fruit of a British-Dutch collaboration. The two countries agreed in 1981 to join forces to build and operate three reflecting telescopes. The first was the existing 2.54-meter INT, refurbished and relocated from Herstmonceux Castle to La Palma, where it saw first light in 1984. A few months later, the new 1-meter Jacobus Kapteyn Telescope joined it, and soon both scopes were in regular use by astronomers visiting from the Netherlands, Spain, and the U.K. The 4.2-meter William Herschel Telescope (WHT) was the third to come out of this collaboration.

Working conditions for astronomers in those pioneering days weren’t as comfortable as they are now. Getting to the observatory from sea level required a one-hour drive up a winding dirt track, often in a thick cloud of orange dust thrown up by any leading vehicles. On the mountaintop, staff and observers initially slept in Spartan huts below the INT building, and meals for the 30 staff members and observers came from the

13 The number of telescopes on the Observatorio del Roque de los Muchachos



Isaac Newton Telescope

WEBSITE: www.ing.iac.es

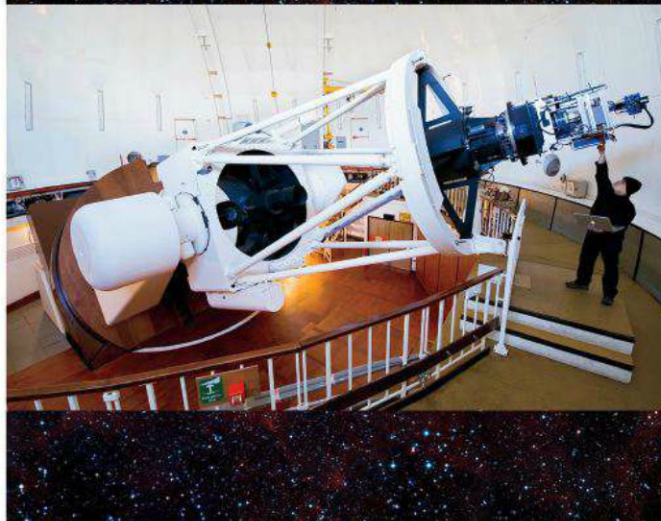
TOURS: 10 A.M. to 1 P.M. every day in the summer, and 10 A.M. to 1 P.M. Tuesdays, Thursdays, and Saturdays the rest of the year (reservations required)

TELESCOPE:

- 2.54-meter optical Isaac Newton Telescope

THE CRESCENT NEBULA (NGC 6888), as seen in this Isaac Newton Telescope photo, formed when a Wolf-Rayet star’s winds slammed into previously ejected gas.

DANIEL LÓPEZ (IAC)



THE ISAAC NEWTON TELESCOPE was the first large instrument on La Palma, although its 2.5-meter mirror now ranks it fifth in size on the island. MAX ALEXANDER

CANARY ISLANDS SCOPES



THE GRAN TELESCOPIO CANARIAS rises above one of the two **MAGIC** telescopes on La Palma. **MAGIC** observes Cerenkov light emitted when cosmic gamma rays strike Earth's atmosphere.

ROBERT WAGNER (MAX-PLANCK-INSTITUT FÜR PHYSIK, MÜNCHEN)



LA PALMA sits at the western edge of the Canary Islands, which in turn sit off the northwestern coast of Africa. *ASTRONOMY: ROEN KELLY AND RICK JOHNSON*

tiny INT kitchen. By 1985, hotel-style living quarters became available.

The 4.2-meter WHT was the third-largest scope in the world at the time of first light in June 1987, and it was designed to gather photons from the faintest and most distant objects known. The mirror's size comes from Owens-Illinois' pre-existing 4-meter mirror mold, whose diameter increased slightly each time a mirror was chipped out. WHT's was the third they made — hence the 4.2. The mold produced a near-perfect paraboloid mirror, however, deviating from the required shape by less than $\frac{1}{3,000}$ millimeter.

Despite it being the norm for most large telescopes nowadays, the WHT's alt-azimuth mount was something of a novelty back then. The construction is cheaper for this kind of mount than for an equatorial design, and the alt-azimuth

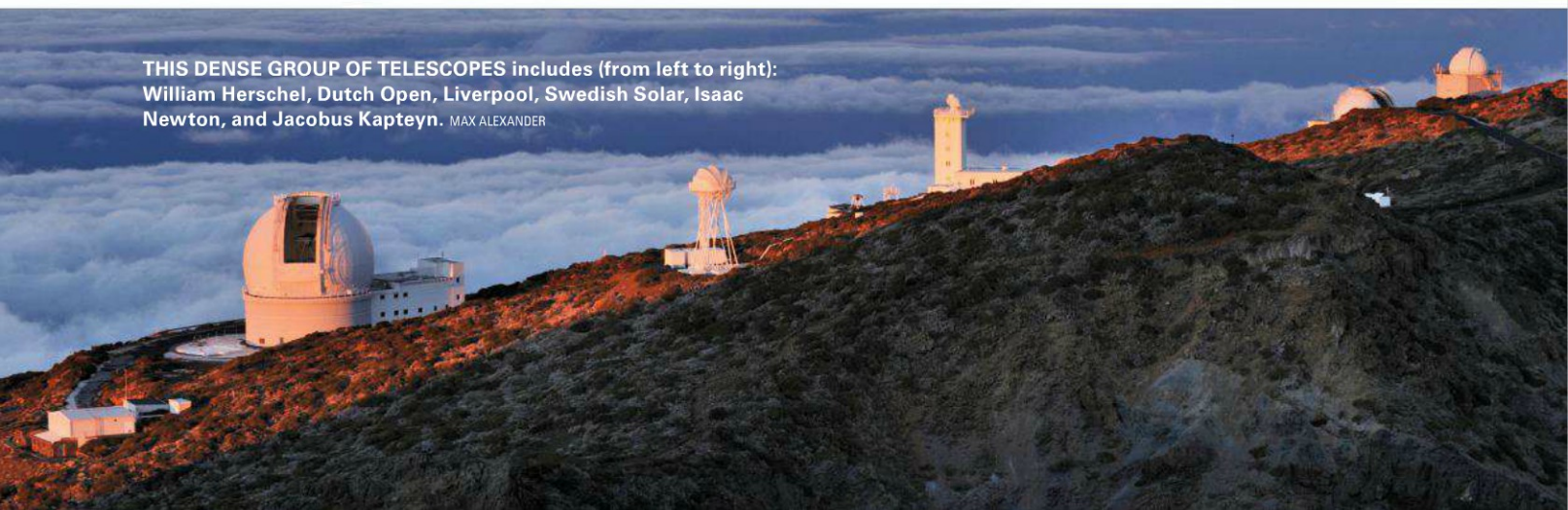
also allows for two Nasmyth foci, where detectors can collect the light. These are ideal for experimental cameras that the astronomer can adjust while observing, and those not robust enough to swing about on the back end of the telescope. The design has provided an opportunity to test many innovative observing techniques at the WHT, such as a prototype of an ambitious adaptive-optics camera for the planned 40-meter European Extremely Large Telescope (see page 53).

The WHT's multiple focal stations give astronomers greater control over how they use their time at night. It takes only a few minutes to switch between the various focal stations, so astronomers can respond rapidly to, say, a change of weather that requires switching to a backup observing program, or an "override" request for an image of a newly discovered supernova.

For 25 years, the WHT has been one of the most scientifically productive 4-meter telescopes in the world. To maintain its competitive edge, plans are now afoot to build a powerful new camera for it. The WHT Enhanced Area Velocity Explorer (WEAVE) will be a multi-object spectrograph, able to observe up to 1,000 stars and galaxies in a single exposure. After WEAVE sees first light in 2016, the WHT will spend much of its time carrying out surveys of millions of stars and galaxies.

One of the most important of these surveys will complement results from the European Space Agency's upcoming Global Astrometric Interferometer for Astrophysics (GAIA) satellite. GAIA will map the three-dimensional positions of a billion stars in our galaxy, and WEAVE will measure the velocities of a large sample of them. Knowing the current positions and motions of the stars,

THIS DENSE GROUP OF TELESCOPES includes (from left to right): William Herschel, Dutch Open, Liverpool, Swedish Solar, Isaac Newton, and Jacobus Kapteyn. *MAX ALEXANDER*

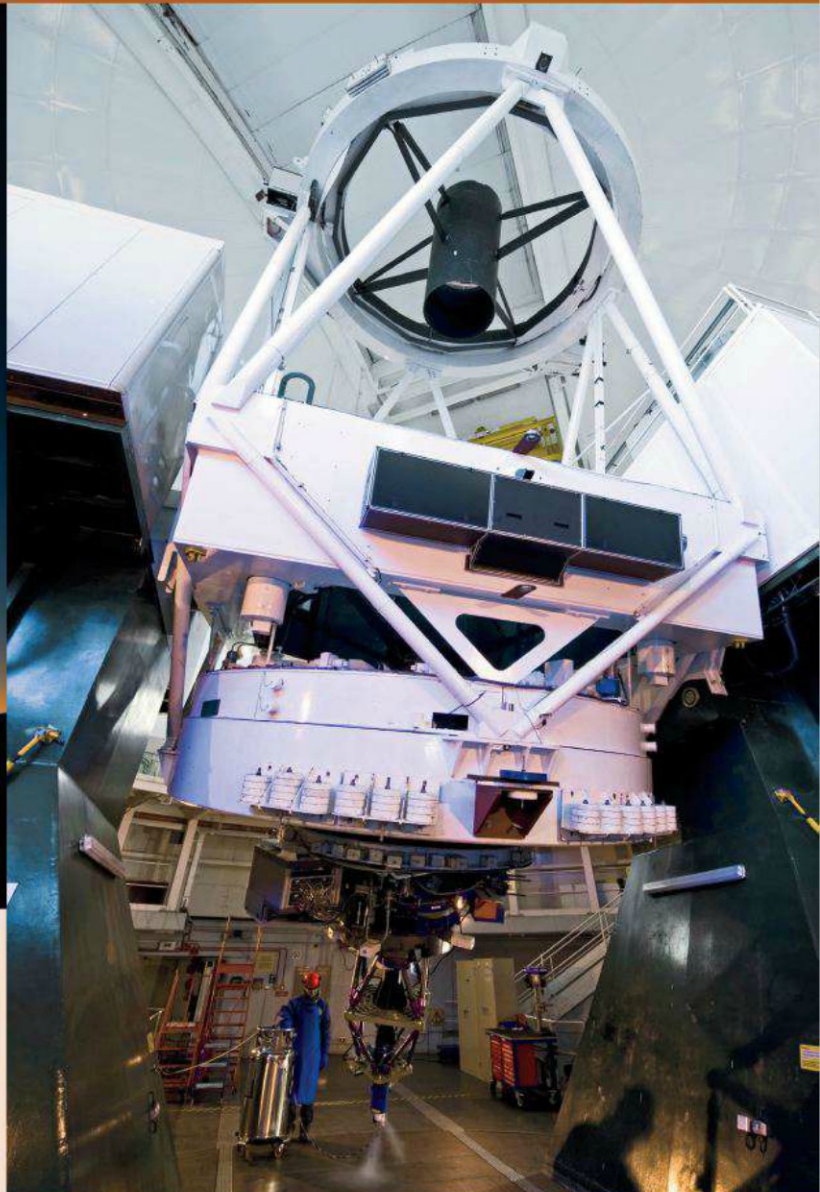


The WHT's namesake, Sir William Herschel, discovered Uranus in 1781.



▲ A CRESCENT MOON hangs above the dome of the William Herschel Telescope (left) and the open-truss structure of the robotic 2-meter Liverpool Telescope. MAX ALEXANDER

► THE 4.2-METER WILLIAM HERSCHEL TELESCOPE was the third largest in the world when it saw first light in 1987 (it currently ranks number 21). Ten years later, it detected the first optical afterglow from a gamma-ray burst. MAX ALEXANDER



SPIRAL GALAXY NGC 7217 shows tightly wound arms and a ring of star formation in this William Herschel Telescope image. MISCHA SCHIRMER (ING) AND GILLES BERGOND (IAA, GRANADA)



STARBURST GALAXY M82 generates plumes of glowing hydrogen, which appear red in this William Herschel Telescope image. PABLO RODRÍGUEZ-GIL (IAC) AND PABLO BONET (IAC)

William Herschel Telescope

WEBSITE: www.ing.iac.es

TOURS: 10 A.M. to 1 P.M.

every day in the summer,

and 10 A.M. to 1 P.M.

Tuesdays, Thursdays, and

Saturdays the rest of the year
(reservations required)

TELESCOPE:

- 4.2-meter optical/near-infrared William Herschel Telescope

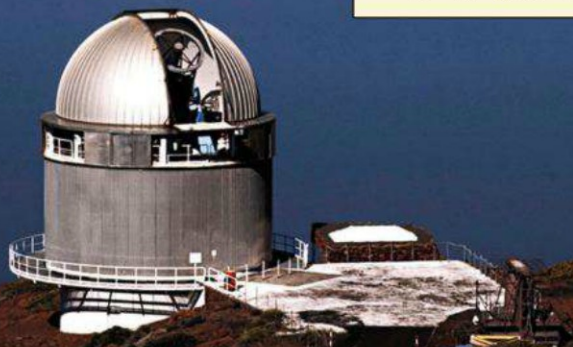
Nordic Optical Telescope

WEBSITE: www.not.iac.es

TOURS: 10 A.M. to 1 P.M. every day in the summer, and 10 A.M. to 1 P.M. Tuesdays, Thursdays, and Saturdays the rest of the year (reservations required)

TELESCOPE:

- 2.56-meter optical Nordic Optical Telescope



THE 2.56-METER NORDIC OPTICAL TELESCOPE is a collaboration among Denmark, Finland, Iceland, Norway, and Sweden. It sits near the Caldera de Taburiente's summit at a spot known for steady atmospheric conditions. IAC'S PHOTO ARCHIVE

The TNG is named for Italian scientist Galileo Galilei, the first to turn a telescope to the heavens.

Telescopio Nazionale Galileo

WEBSITE: www.tng.iac.es

TOURS: 10 A.M. to 1 P.M. every day in the summer, and 10 A.M. to 1 P.M. Tuesdays, Thursdays, and Saturdays the rest of the year (reservations required)

TELESCOPE:

- 3.58-meter optical/infrared Telescopio Nazionale Galileo



ITALY'S 3.58-METER TELESCOPIO NAZIONALE GALILEO, modeled on Chile's New Technology Telescope, is La Palma's third-largest optical scope. GIOVANNI TESSICINI (TNG)

astronomers can then effectively reverse time and learn the events that led to the Milky Way's current conditions.

The growing family

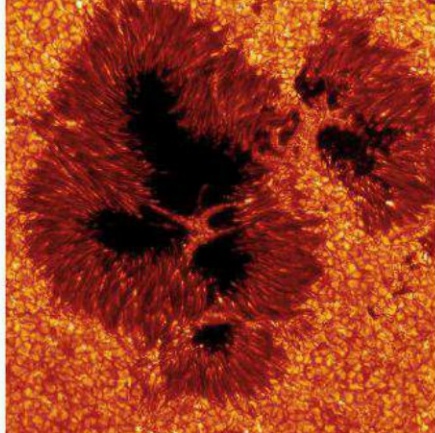
Over the past 30 years, many countries have brought their telescopes to the ORM. Denmark, Finland, Iceland, Norway, and Sweden have operated their 2.56-meter Nordic Optical Telescope (NOT) since its first light in 1988 upon a windswept perch close to the summit, a location renowned for its excellent seeing. A little lower down, the Italians have their 3.58-meter Telescopio Nazionale Galileo (TNG), which saw first light in 1998; it's modeled closely on the European Southern Observatory's New Technology Telescope in La Silla, Chile (see page 44).

Other additions include the British Liverpool Telescope (a robotic 2-meter instrument); the Belgian Mercator Telescope (a 1.2-meter scope); the British Super Wide Angle Search for Planets, or SuperWASP (two sets of eight camera arrays); and the German Major Atmospheric Gamma-ray Imaging Cerenkov array, or MAGIC (two 17-meter gamma-ray telescopes) — not to mention the record-breaking Spanish 10.4-meter, the Gran Telescopio Canarias!

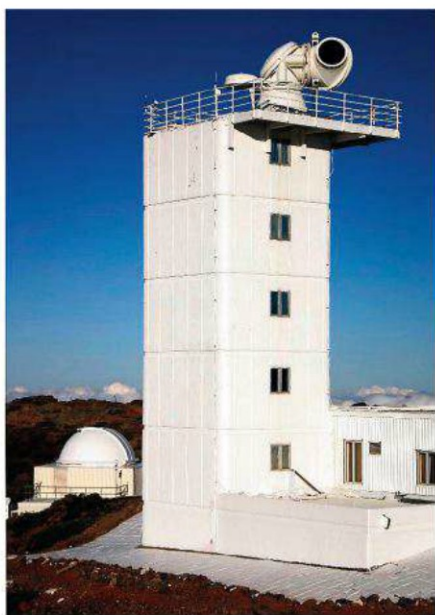
During the day, the twin 17-meter eyes of the MAGIC telescopes gaze sightlessly at the northern horizon. Tourists driving past often slow to a halt to take photos and puzzle over the huge white buildings reflected in each telescope. In fact, there are no white buildings — just 17-meter distortions of the nearby detector boxes at the focus of each dish.

At night, the dishes search for brief flashes of Cerenkov light that signal the impact of gamma rays with Earth's atmosphere. MAGIC can deduce where in the sky the light waves came from, and it studies some of the universe's most energetic and mysterious phenomena, such as supernova remnants and distant quasars.

But deep-sky objects aren't all that the clear, calm skies above La Palma offer astronomers: Conditions are also perfect for studying the Sun. The 1-meter Swedish Solar Telescope (SST) often zooms in on sunspots large enough to dwarf our planet. Thanks to the use of adaptive optics, which cancel out some of the blurring introduced by Earth's atmosphere, the SST delivers



FILAMENTARY SUNSPOTS and solar granulation come to light in this view taken through the Swedish Solar Telescope. MATS LÖFDAHL/ROYAL SWEDISH ACADEMY OF SCIENCES



THE SWEDISH SOLAR TELESCOPE, whose 1-meter primary lens (inside the structure at top) makes it the world's second-largest solar scope, takes exquisitely sharp images of our nearest star. TIM VAN WERKHOVEN

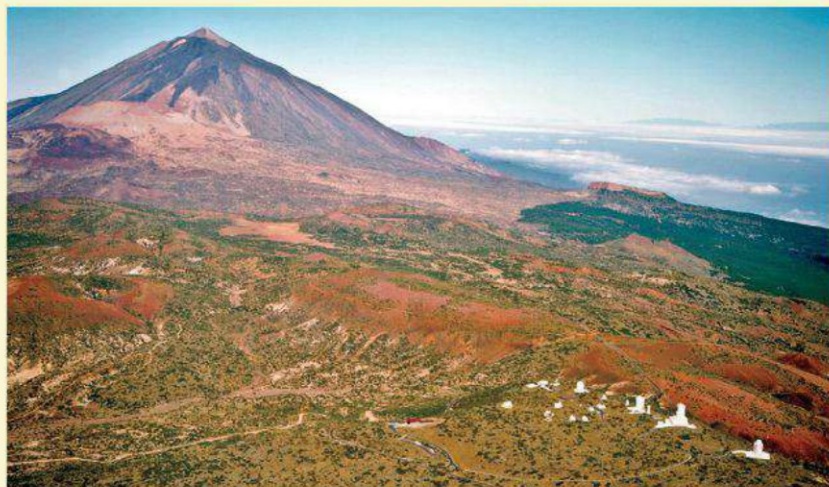
sharper solar images than any other telescope in the world.

All together, the various optical telescopes provide astronomers with an impressive toolkit. Need to monitor the brightness of a star? Just use the Liverpool Telescope. Multi-object infrared spectroscopy? Then you'd want the WHT. The telescopes are nominally national facilities, but in practice most European astronomers can compete for time on the majority of the instruments.

The different national organizations employ a staff of about 170 representing various countries to run the telescopes. They work partly at the observatory and partly in offices in or around the island's main town, Santa Cruz de La Palma. The ORM is a truly international collaboration on all levels.



The neighboring observatory



OBSERVATORIO DEL TEIDE sits on the flanks of 12,000-foot (3,700 meters) Mount Teide on Tenerife, southeast of La Palma in the Canary Islands. IAC'S PHOTO ARCHIVE

Some 87 miles (140 kilometers) southeast of the Observatorio del Roque de los Muchachos lies the 12,000-foot (3,700 meters) peak of Mount Teide on the nearby island of Tenerife. Here, the sky is not as dark as it is above La Palma, thanks to Tenerife's large population and booming tourism industry. But the seeing and

transparency are still excellent, and Observatorio del Teide boasts several solar telescopes and some small nighttime telescopes.

The 89-mile (144km) line of sight across the Atlantic Ocean between La Palma and Tenerife islands creates an interesting opportunity for testing various technologies. The most

exotic experiment yet took place in 2007 when a team from the University of Vienna transmitted quantum-entangled photons from La Palma to Tenerife, setting a world distance record. These experiments pave the way for secure transmission of encryption keys over distances and other futuristic technology.

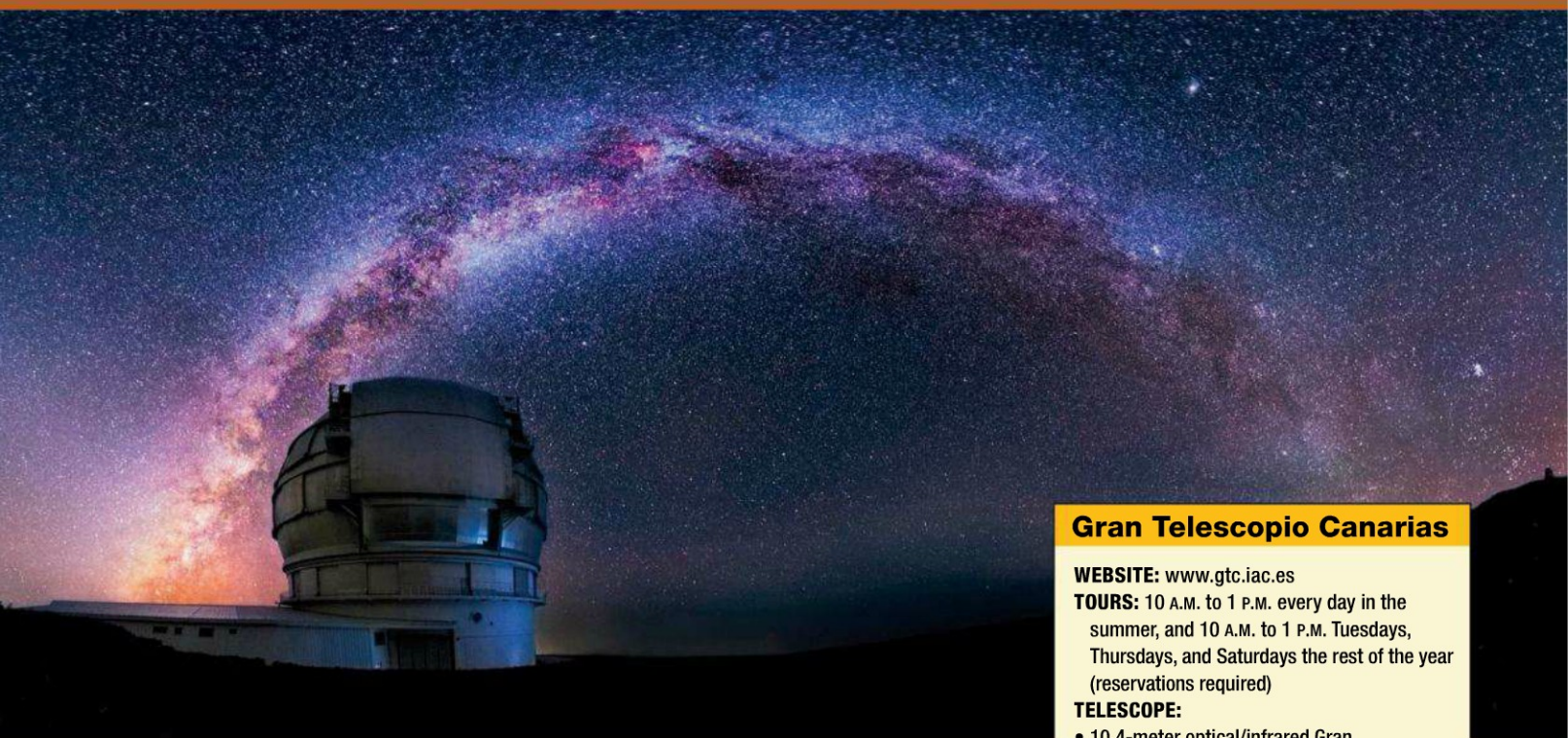
King of the mountain

In the mid-1990s, La Palma still lacked an 8- to 10-meter telescope, so the Instituto de Astrofísica de Canarias (IAC) in Tenerife, which operates the ORM, launched a project to build one. The Spanish and Canarian governments initially provided funding, with Mexico and the University of Florida later joining in. It took a while, but first light occurred in July 2007, and science observations at the Gran Telescopio Canarias (GTC) formally began in July 2009 with an inauguration by Spain's King Juan Carlos I.

The GTC's primary mirror measures 10.4 meters, making it the largest single-aperture optical telescope in the world — and it can actually observe infrared light, as well. The mirror, modeled on the successful telescopes at Hawaii's Keck

Observatory (see page 18), is made up of 36 hexagonal segments. Each segment is made of a ceramic material famed for its ability to avoid expanding and contracting with changing temperature.

Unlike the WHT, with its paraboloid primary mirror, the GTC's mirror is hyperboloid in shape, allowing for a Ritchey-Chretien telescope design that offers a wider field of view. The secondary mirror is made of beryllium, a lightweight, high-rigidity metal capable of withstanding the rigors of observing in the infrared. Like most modern telescopes, the GTC has an alt-azimuth mount. Its two Nasmyth platforms host its Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS) visual camera, as well as its CanariCam mid-infrared camera.



THE MILKY WAY arches above the Gran Telescopio Canarias, whose 10.4-meter mirror makes it the world's largest single-aperture optical telescope. DANIEL LÓPEZ AND THE IAC'S PHOTO ARCHIVE

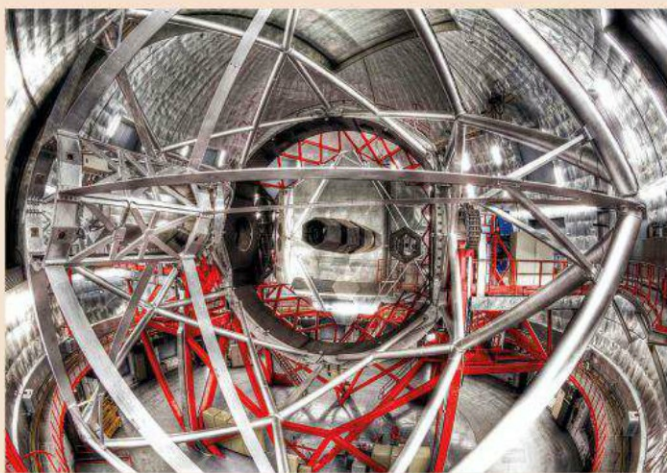
Gran Telescopio Canarias

WEBSITE: www.gtc.iac.es

TOURS: 10 A.M. to 1 P.M. every day in the summer, and 10 A.M. to 1 P.M. Tuesdays, Thursdays, and Saturdays the rest of the year (reservations required)

TELESCOPE:

- 10.4-meter optical/infrared Gran Telescopio Canarias



THE HUGE 10.4-METER MIRROR of the Gran Telescopio Canarias consists of 36 hexagonal segments and was modeled after the twin Keck telescopes on Mauna Kea, Hawaii. PABLO BONET AND THE IAC'S PHOTO ARCHIVE



TWIN LOBES OF GAS rush from a hot star embedded in emission nebula Sharpless 2-106, as seen in this shot from the Gran Telescopio Canarias. GRAN TELESCOPIO CANARIAS AND IAC

OSIRIS was the first scientific instrument on the scope, and the IAC designed and built it. The camera features tunable filters, devices that transmit a small range of wavelengths. By taking repeated exposures while slowly varying the transmitted wavelength, astronomers can obtain spectra of large regions such as galaxies or nebulae in one go.

The University of Florida produced the CanariCam, which allows astronomers to

obtain images and spectra of a specific range of infrared light (wavelengths of 7.5 to 25 microns). Such data is crucial for understanding star formation because the process often takes place within dense molecular clouds that absorb optical wavelengths but allow infrared waves through.

The construction of the GTC proved to be a powerful catalyst for Spanish industry, which handled about 70 percent

of the physical labor in building the telescope, dome, and instruments. The telescope's completion is another landmark in the rapid development of Spanish astronomy, which in 30 years has grown from almost nothing to become one of the premier European forces in the field.

The scientific fruits

With such a powerful plethora of telescopes at the ORM, it's no surprise that



THIS EIGHT-CAMERA ARRAY — known as the Super Wide Angle Search for Planets (SuperWASP) — monitors millions of stars in the search for worlds outside our solar system. By the start of 2012, SuperWASP already had nabbed 65 planets. MAX ALEXANDER

many of them should play a powerful role in the advance of astronomy. For instance, the discovery that the expansion of the universe is accelerating — one of the greatest remaining unsolved puzzles in physics — owes a lot to La Palma's telescopes. The two teams of astronomers who won the 2011 Nobel Prize in physics for this discovery made use of the INT, WHT, and NOT to measure the increasingly far-off distances to extragalactic supernovae. This provided the evidence for the existence of a mysterious "dark energy" that somehow accounts for 72 percent of the stuff in the universe, but whose nature remains unknown.

Another of La Palma's contributions to science has to do with one of the biggest enigmas of the 1990s: the nature of gamma-ray bursts (GRBs) — puzzling flashes of light first detected by American satellites checking for evidence of clandestine nuclear tests. Nobody had seen an optical counterpart to a GRB, but such a sight would be crucial to find out how far away they are. Several telescopes at the ORM were part of coordinated campaigns to detect these bursts optically. On February 28, 1997, the WHT struck gold, catching the optical afterglow of a GRB before it faded. Since then, astronomers have detected many more in visible light, and they now suspect that the phenomena are associated



Students, visitors welcome

Unlike the national telescopes of yesterday, most of today's cutting-edge light buckets (such as the ones in Hawaii and Chile [see pages 18 and 44]) lie far away from their users. In addition, time on them is so precious that local staff, or computer programs, do much of the observing, juggling different projects during the night so as to match them to the prevailing conditions. These two factors make it more difficult for young astronomers to get hands-on training at a research telescope.

By contrast, the telescopes on La Palma are relatively accessible, and students are frequent observers. They also get work as support astronomers at both the 2.54-meter Isaac Newton Telescope (INT) and the 2.56-meter Nordic Optical



STUDENTS GET HANDS-ON TRAINING at the Roque de los Muchachos Observatory. Here, two of them help operate the 2.5-meter Isaac Newton Telescope in support of visiting astronomers. ING

Telescope. The former recruits four students each autumn, who live on La Palma for the next year; they typically spend 40 percent of their time supporting visiting observers at the INT and working on other observatory duties, and the rest of the time pursuing their own research. Outside of work, they get to learn a new language, immerse themselves in the local culture, and explore La Palma's

natural wonders. Over the past 10 years, some 40 students from seven different countries have taken part in this popular program.

Interested tourists are also welcome at the observatory. La Palma receives daily flights from Madrid, Spain, and the larger Canary Islands, and less frequently from other European countries. For details on taking a tour of the facility, visit www.iac.es.

with unusually violent star deaths in distant galaxies. Because of their intense brightness, GRBs are visible from incredible distances; Italy's TNG spotted one in 2009 with a record-breaking redshift of 8.1 — about 13.1 billion light-years away.

But not all of La Palma's science successes are extragalactic and energetic. The ORM's SuperWASP is one of the most prolific planet-hunters in the world, watching for regular dips in stars' brightnesses, which happen whenever planets pass in front of them. Many of the ORM's telescopes were useful when it came time to study these transits in more detail, and in 2009, the WHT obtained the first ground-based direct detection of an extrasolar planet in the near-infrared visual spectrum.

The WHT, until 2007 the most powerful telescope on the mountain, has scored many other firsts, obtaining the deepest ground-based image of the sky, the first spectrum of a near-Earth object that subsequently hit our planet, the first optical images of the surface of a star other than the Sun, the first detection of a brown dwarf, and the first strong evidence of black holes in our galaxy. And with the GTC now up and running, who knows what kinds of amazing discoveries the ORM's scopes will make?

The island of La Palma has seen pirate attacks, Spanish conquistadors, scientific breakthroughs, and pioneering astronomers. It's clear that a place with so much history will continue to make more of it for years to come. ☼

THE REST OF THE WORLD

The best of

I

t's no surprise that astronomers seek sites with clear dark skies and a steady atmosphere. These conditions promote year-round observing and deliver sharp images. A look at where the big scopes lie (see page 16) shows such sites are not common. Most 2.5-meter and larger instruments are in the southwestern United States, Chile, Hawaii, and the Canary Islands. Asia, Africa, and Australia each have only one, and continental Europe just a handful. Although they may not be plentiful, these instruments are still worth exploring.

STARS CIRCLE the South Celestial Pole behind the dome of the 3.9-meter Anglo-Australian Telescope. AUSTRALIAN ASTRONOMICAL OBSERVATORY, PHOTOGRAPH BY DAVID MALIN



the rest Earth's other giant telescopes

Some of the largest scopes in the world scan the skies above Australia, South Africa, Russia, and other stellar sites.

By Richard Talcott

Australia

Optical astronomy Down Under followed a trajectory similar to that blazed in the United States and Europe.

Astronomers initially placed observatories at sites where convenience outweighed isolation. Australia's Sydney Observatory mimicked other pioneering locations such as France's Paris Observatory, England's Royal Greenwich Observatory on the outskirts of London, and Harvard College Observatory in suburban Boston, Massachusetts.

By the start of the 20th century, Australian astronomers set their sights a bit farther afield. In 1924, the government established the forerunner of what would become Mount Stromlo Observatory in the western suburbs of the capital city, Canberra. In 1954, the observatory erected a reflecting telescope with a 74-inch-diameter (1.9 meters) mirror. For the next 20 years, it would reign as the Southern Hemisphere's largest telescope. It joined two other sizable instruments — a

50-inch and a 30-inch reflector — as well as several smaller ones.

Although the sky above Canberra's Mount Stromlo isn't the best, that's not what brought the demise of observational astronomy there. On January 18, 2003, a massive bush fire hit the observatory and damaged or destroyed most of it. All of the big scopes were lost; only a historic 6-inch refractor dating from the 19th century survived. Today, the observatory is headquarters of the Australian National University's Research School of Astronomy and Astrophysics. The observatory's visitor center is closed indefinitely, but people can take self-guided walking tours of the grounds.

The mecca of Australian observational astronomy now lies on the edge of the picturesque Warrumbungle National Park some 17 miles (27 kilometers) west of Coonabarabran, a small town in northern New South Wales. Siding Spring Observatory lies 3,822 feet (1,165m) above sea level and still enjoys dark skies. The Australian National University selected this site in the 1960s as conditions around Mount Stromlo deteriorated.

Richard Talcott is an Astronomy senior editor and author of *Teach Yourself Visually Astronomy* (Wiley Publishing, 2008).

Siding Spring Observatory

LOCATION:

Coonabarabran, Australia

WEBSITE:

<http://msowww.anu.edu.au/info/sso>

VISITORS WELCOME:

9:30 A.M. to 4 P.M.

Monday–Friday; 10 A.M.

to 4 P.M. Saturday and

Sunday

TELESCOPES:

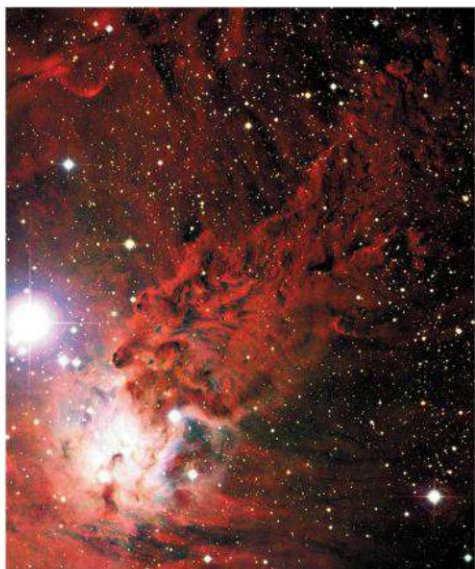
- 3.9-meter Anglo-Australian Telescope
- 2.3-meter Advanced Technology Telescope
- 2-meter Faulkes Telescope South
- 1.3-meter SkyMapper Telescope
- 1.2-meter UK Schmidt Telescope

The giant of Siding Spring is the 3.9-meter Anglo-Australian Telescope (AAT). At first light in 1974, the scope ranked as the world's third largest and the biggest south of the equator. (It would lose its preeminence to the 4-meter Victor M. Blanco Telescope on Cerro Tololo, Chile, two years later.) As its name suggests, this instrument is a joint venture of the British and Australian governments.

While workers were building the AAT, the British also constructed the 1.2-meter UK Schmidt Telescope. With its 6.6° field, the Schmidt is perfect for wide-field photography. Its southern sky survey complemented one of the northern sky conducted by a similar telescope at California's Palomar Observatory.

Several other telescopes call Siding Spring home. The biggest is the 2.3-meter Advanced Technology Telescope. Built in the early 1980s, it was the first instrument to combine a thin mirror, a mount that moves in both altitude and azimuth, and a rotating building. The 2-meter robotic Faulkes Telescope South is a twin of one at Hawaii's Haleakala Observatory, and both are copies of the Liverpool Telescope on La Palma in the Canary Islands (see page 54).

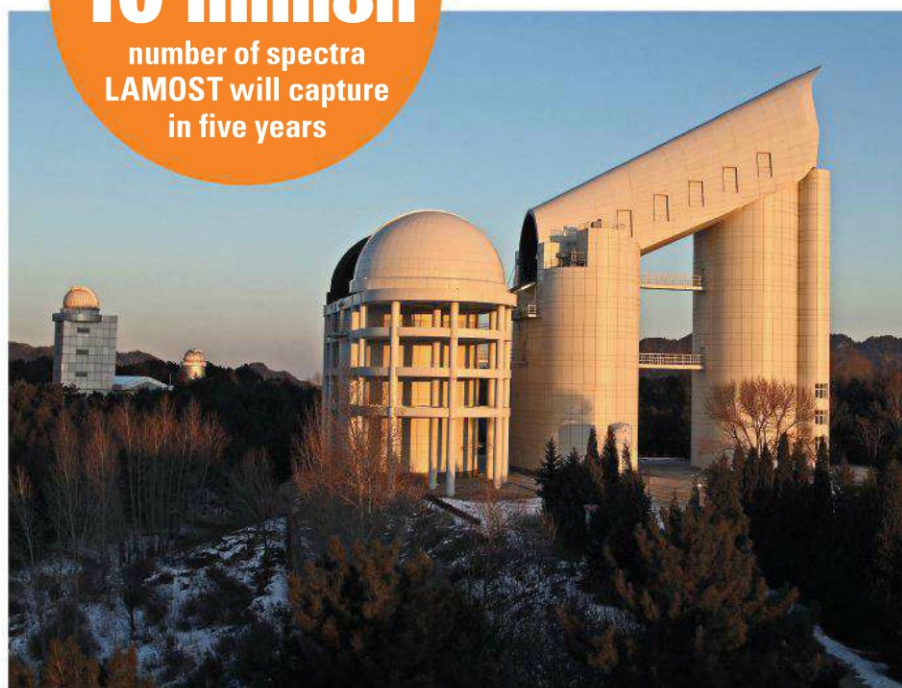
Siding Spring Observatory is open to the public throughout the year except for Christmas Day and Boxing Day. It features a visitor's center and gift shop as well as a viewing gallery from which to see the 3.9-meter AAT. 🌌



THE FOX-FUR NEBULA (NGC 2264) glows red under intense ultraviolet radiation coming from the hot star S Monocerotis (at far left). Imager David Malin captured this scene through the 3.9-meter Anglo-Australian Telescope. AUSTRALIAN ASTRONOMICAL OBSERVATORY, PHOTOGRAPH BY DAVID MALIN

10 million

number of spectra
LAMOST will capture
in five years



CHINA'S LAMOST, an acronym for Large Sky Area Multi-Object Fiber Spectroscopic Telescope, is a 4-meter instrument designed to take spectra.

Asia

If you head about 100 miles (160 kilometers) north-east of Beijing, China, you'll reach the home of the National Astronomical Observatory of China at Xinglong Station. The site sits at an altitude of 3,150 feet (960 meters) and boasts four telescopes with apertures of at least 1 meter, including a 1.3-meter instrument optimized for infrared studies and a 2.2-meter optical telescope.

But the newest and biggest telescope there is the 4-meter Large Sky Area Multi-Object Fiber Spectroscopic Telescope, or LAMOST for short. (It also goes by the name Guoshoujing Telescope after a prominent Chinese scientist of the 13th and 14th centuries.) The instrument looks like no other in the world. It consists of a long slanted

tube that rests on two towers and a domed building that houses the primary mirror. If it looks slightly unwieldy, it is — it can point only in one direction. Here's how it works.

The structure remains fixed along a north-south axis (the meridian). The domed building contains the 4-meter primary mirror, which operators can move so it points up to about 30° away from the meridian. Because Earth rotates beneath the sky, the scope can view nearly the entire northern part of the heavens; it just can't stay focused on a specific area for more than a few hours at a time.

Incoming light bounces off the primary mirror up the tube to a secondary mirror, which reflects the light back down the tube and focuses it on an array of

4,000 optical fibers.

Both mirrors consist of multiple hexagonal segments whose shape can be adjusted on the fly to eliminate the effects of poor seeing and render sharp images.

Each of the robotically positioned fibers points toward a star or galaxy that astronomers want to study. The fibers then feed all of the objects' light into 16 different spectrographs located in a room on the lower floor of the tower that lies closest to the domed structure.

The unique design offers a 5° field of view, some 10 times the Full Moon's diameter, so LAMOST can survey the sky efficiently. By taking 4,000 spectra at a time, the scope captures 10,000 stars or galaxies in a single night and more than 2 million objects during a typical year (which features

National Astronomical Observatory of China

LOCATION: Xinglong Station, China

WEBSITE: <http://lamost.us/league>

TELESCOPES:

- 4-meter LAMOST
- 2.2-meter telescope
- 1.3-meter infrared telescope
- 1-meter telescope

NATIONAL ASTRONOMICAL OBSERVATORY OF CHINA

South African Astronomical Observatory

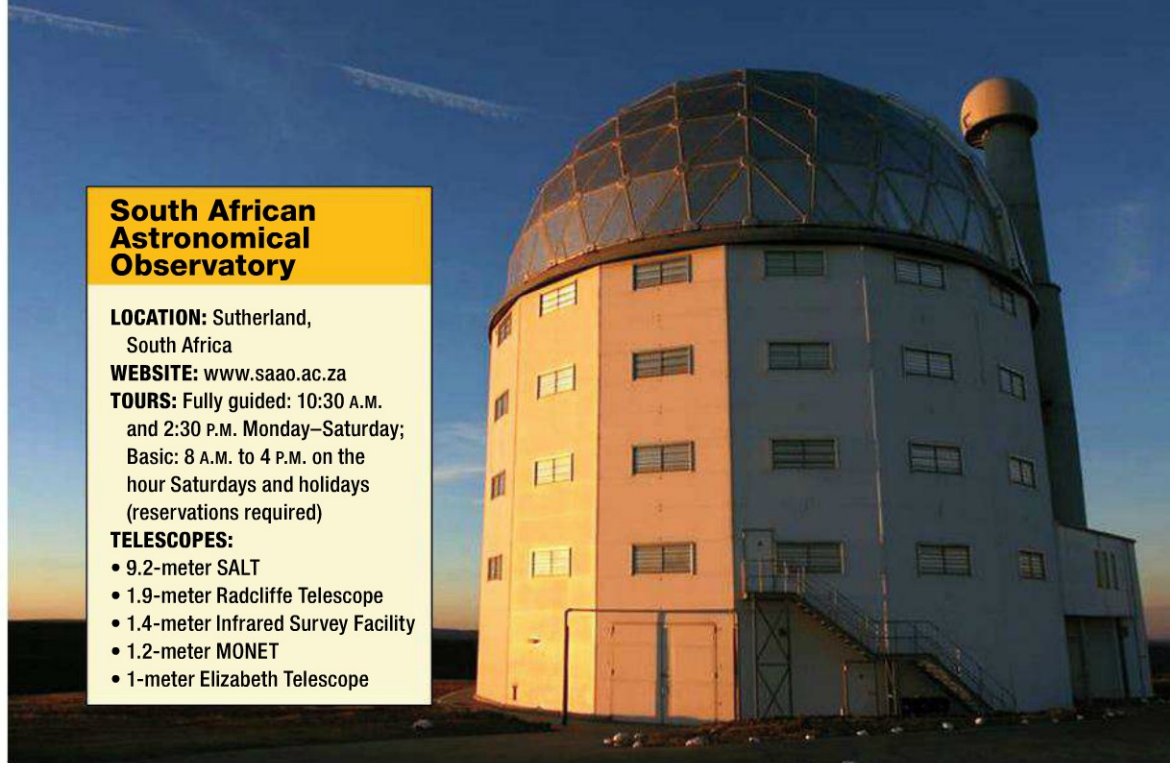
LOCATION: Sutherland, South Africa

WEBSITE: www.saa.ac.za

TOURS: Fully guided: 10:30 A.M. and 2:30 P.M. Monday–Saturday; Basic: 8 A.M. to 4 P.M. on the hour Saturdays and holidays (reservations required)

TELESCOPES:

- 9.2-meter SALT
- 1.9-meter Radcliffe Telescope
- 1.4-meter Infrared Survey Facility
- 1.2-meter MONET
- 1-meter Elizabeth Telescope



The South African Large Telescope, a 9.2-meter behemoth that is the Southern Hemisphere's largest optical telescope, was modeled after the Hobby-Eberly Telescope at Texas' McDonald Observatory. Although the two share a similar optical design, the domes look entirely different. JANUS BRINK (SAAO)

Africa

about 210 clear nights, on average).

The telescope's major scientific thrust is the LAMOST Experiment for Galactic Understanding and Exploration (LEGUE). By collecting spectra of millions of stars in the Milky Way, the survey will detail the motions and compositions of 10 times as many objects as any previous study.

Among other results, this information will allow astronomers to analyze the many stellar streams flowing through the galaxy's halo. By mapping these streams — remnants of dwarf galaxies destroyed by the Milky Way's strong tidal forces — LEGUE should help map the dark matter halo that surrounds the Milky Way. ☼

5,899

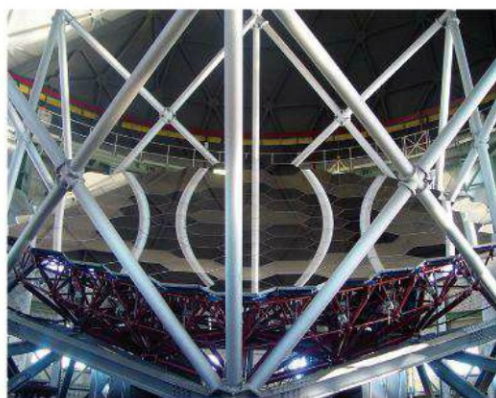
altitude, in feet, of
SALT (1,798 meters)

The largest telescope in the Southern Hemisphere scans the sky from near Sutherland, South Africa, a town situated some 225 miles (360 kilometers) northeast of Cape Town. The South African Large Telescope (SALT) sits on the grounds of the South African Astronomical Observatory (SAAO) along with about a dozen other research instruments. With an effective aperture of 9.2 meters, however, SALT rises far above the rest.

This instrument bears a striking resemblance to the Hobby-Eberly Telescope (HET) at McDonald Observatory in Texas (see page 32). In fact, SALT began as a copy of the HET. Both have primary mirrors made from 91 hexagonal segments, each of which measures 3.9 feet (1.2m) across. Both capture decent images, but they really shine when taking spectra.

Yet SALT's designers decided to alter the optical system to give the southern telescope a slightly wider field of view. SALT points toward a fixed elevation of 53°, but its design allows it to swing in azimuth to view objects across most of the southern sky.

Construction ended in 2005, but some problems with image quality showed up during the scope's



THE MIRROR of the South African Large Telescope comprises 91 hexagonal segments joined in a matrix 11.1 meters by 9.8 meters. Because it can point only in one direction, however, it has an effective aperture of 9.2 meters. SALT CONSORTIUM

commissioning phase. Operators took SALT off-line and corrected the flaw, returning the scope to service in 2010.

Visitors to South Africa who have an astronomical bent will want to see SALT and its neighbors at the SAAO. Be sure to plan ahead. Tours must be booked in advance and accommodate a maximum of 25 people. Fully guided tours occur Monday through Saturday at 10:30 A.M. and 2:30 P.M. and cost 30 rand per person. They stop at SALT and other research telescopes. Basic tours take place on Saturdays and holidays from 8 A.M. to 4 P.M., every hour on the hour. They cost 20 rand per person and do include SALT. ☼

Pic du Midi Observatory

LOCATION: Pic du Midi, France

WEBSITE: www.picdumidi.com

VISITORS WELCOME: cable cars depart La Mongie every 15 minutes from 10 A.M. to 3:30 P.M. (October 1–May 31) and 9 A.M. to 4:30 P.M. (June 1–September 30)

TELESCOPES:

- 2-meter Bernard Lyot Telescope
- 1.1-meter telescope

THE PIC DU MIDI OBSERVATORY in southern France rests on a seemingly precarious perch high in the Pyrenees. Visitors can reach the summit either by cable car or on foot (although be prepared for a relative lack of oxygen compared with sea level). PASCAL PETIT (IRAP)

Europe

It may seem odd that Europe, the continent where observational astronomy was born, has such a dearth of large telescopes. It wasn't always that way. In fact, Europe claimed the world's biggest telescope from the early 17th century until the second decade of the 20th century. As astronomers wanted bigger and better telescopes and desired to place them at pristine sites, however, mainland Europe fell out of favor. European countries continued to build giant scopes, but they did it offshore (in the Canary Islands) and in the Southern Hemisphere (Chile).

The biggest telescope in continental Europe lies in Russia. The 6-meter Bolshoi Azimuthal Telescope observes from the northern Caucasus Mountains. When finished in the mid-1970s, it surpassed

Palomar Observatory's 200-inch (5m) Hale Telescope in California as the world's largest. The Bolshoi (Russian for "big") remained at the top of the world heap until Hawaii's 10-meter Keck I Telescope opened in 1993.

Despite its size, or perhaps because of it, the Bolshoi never met expectations. The 42-ton mirror and the huge dome surrounding it make it nearly impossible for the instrument to reach a stable temperature and deliver sharp views. The site is also downwind from several Caucasus peaks, which degrades the astronomical seeing. Conditions deliver a resolution of 1 arcsecond or better on only 20 percent of clear nights, far from what most modern observatories achieve.

Still, the telescope's light-gathering ability lets it image and record spectra of exceptionally faint objects.

The Soviet Union built two other large instruments that continue to operate in former republics: the 2.6-meter Shajn Telescope at the Crimean Astrophysical Observatory in Nauchny, Ukraine, and the 2.6-meter Byurakan Astrophysical Observatory Telescope on Mount Aragatz, Armenia.

Across the continent in Andalucía, Spain, Western Europe's largest telescope looks out from its perch 7,113 feet

(2,168m) above sea level. The 3.5-meter instrument belongs to Calar Alto Observatory, a joint project of Spain's Institute of Astrophysics of Andalucía and

198
Degrees Fahrenheit
at which water boils
on Pic du Midi (92° C)

Germany's Max Planck Institute for Astronomy in Heidelberg. The institutions started collaborating in 1970 when neither country could offer its scientists much access to quality telescopes or clear skies.

The observatory's first telescope arrived in 1975. This 1.2-meter instrument was joined by a 2.2-meter scope in 1979 and, ultimately, the 3.5-meter in 1985. The Observatory of Madrid separately operates a 1.5-meter reflector on the same mountaintop.

If you look at satellite photos of Earth at night, the glow from artificial lighting in Western Europe makes it look like a poor spot for an observatory. But Calar Alto beats the odds. Spain recently enacted light-pollution controls that cover an area of 1,463 square miles (3,788 square km) surrounding the observatory. This is the biggest region with lighting restrictions in Europe.

The future looks bright enough (pun intended) that astronomers plan to build a 6.5-meter telescope on Calar Alto. HEXA will make spectroscopic surveys of the sky. Data from the new instrument should shed more light on the evolution of galaxies and the nature of dark energy, the mysterious force that appears to be accelerating the universe's expansion.

But no trip to the astronomical high-lights of Europe would be complete without a visit to Pic du Midi Observatory. Located high in the Pyrenees of southern France, the observatory offers stunning views of the surrounding mountains.

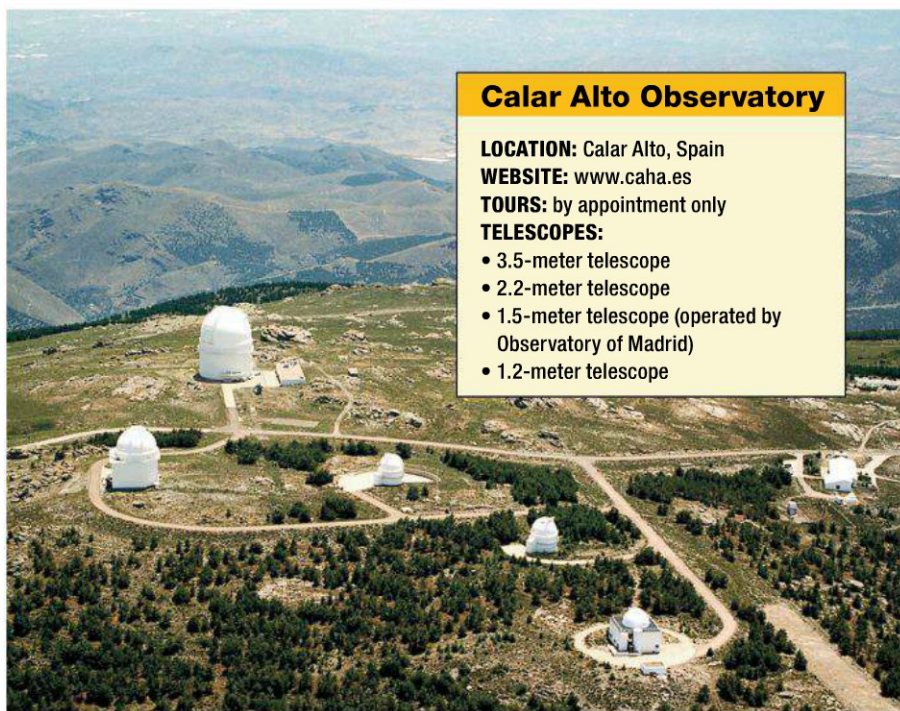
A 15-minute cable-car ride will deliver you to the summit at an elevation of 9,439 feet (2,877m) for a cost of 32 euros. (The adventurous can climb the mountain and ride the cable car back down.) You can even spend the night at the hotel up there, observing the sky with naked eyes and watching the Sun come up.

The observatory's big instruments are the 2-meter Bernard Lyot Telescope, the largest in France, and a 1.1-meter reflector dedicated to solar system observations. NASA funded the latter, which took detailed photos of the Moon's surface in preparation for the Apollo lunar landings.

Visiting Pic du Midi Observatory and the Pyrenees will remind visitors how astronomers seek isolated locations to pursue their passion. And how, occasionally, it can be just as satisfying to look down as to look up to appreciate the beauty of the universe. 🌌



SPIRAL GALAXY NGC 7331 lies some 50 million light-years from Earth. Despite this immense gulf, dark dust lanes, brilliant blue star clusters, and pink clouds of glowing hydrogen show up clearly through the 3.5-meter eye of the Calar Alto Observatory's biggest telescope, located in Spain. CALAR ALTO OBSERVATORY/VINCENT PERIS (OAU)/GILLES BERGOND (CAHA)



Calar Alto Observatory

LOCATION: Calar Alto, Spain

WEBSITE: www.caha.es

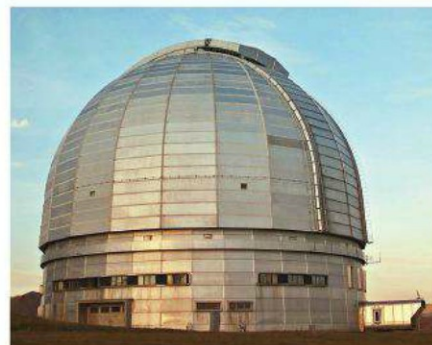
TOURS: by appointment only

TELESCOPES:

- 3.5-meter telescope
- 2.2-meter telescope
- 1.5-meter telescope (operated by Observatory of Madrid)
- 1.2-meter telescope

▲ **THE CALAR ALTO OBSERVATORY** in Andalusia, Spain, boasts the largest telescope in Western Europe (a 3.5-meter reflector housed in the background dome) as well as several smaller instruments. MPIA

► **THE BOLSHOI AZIMUTHAL TELESCOPE** in the Caucasus Mountains of southern Russia was the largest in the world from 1975 until 1993. The huge dome and heavy mirror combine with unstable atmospheric conditions to wreak havoc on its images, however, and the huge scope has never lived up to expectations. TYAVIN PAUL



Astronomy in

Unhindered by Earth's distorting atmosphere, space telescopes bring us our clearest view of the cosmos yet.

By Ray Villard

L

ong before humanity could blast into space, astronomers dreamed of placing a telescope above Earth's obscuring atmosphere. In 1923, German scientist Hermann Oberth proposed a space observatory. Early balloon-, rocket-, and even satellite-borne instruments produced enough scientific revelations to hint at how much could be accomplished from high-altitude and orbital platforms.

In 1946, American physicist Lyman Spitzer wrote a paper titled "Astronomical Advantages of an Extra-terrestrial Observatory." In it, he outlined the advantages of a space-based observatory. Throughout his career, Spitzer pushed for a space telescope. In 1965, he headed a committee that outlined such an instrument's scientific objective.

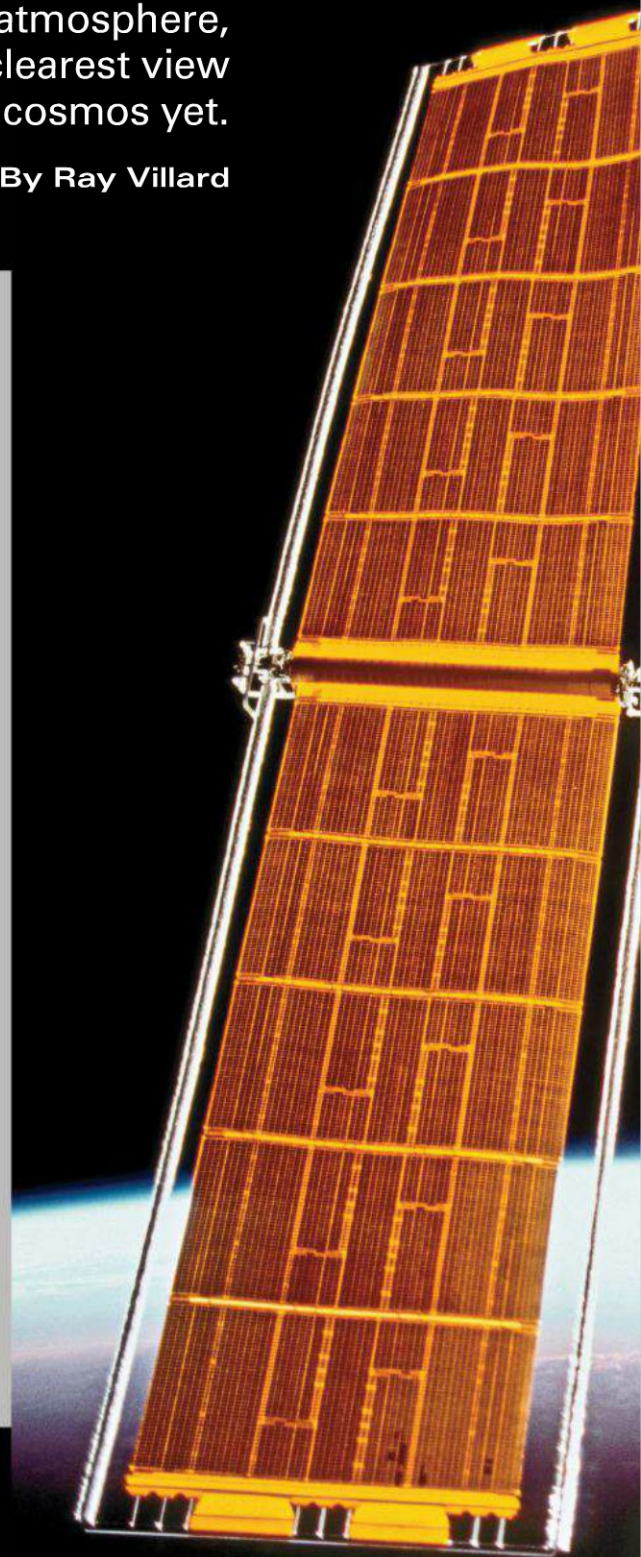
In 1962, just four years after Congress established the National Aeronautics and Space Administration (NASA), a National Academy of Sciences (NAS) study group recommended the development of a large space telescope. Even then, NAS saw this as a long-range goal of the country's fledgling space program.

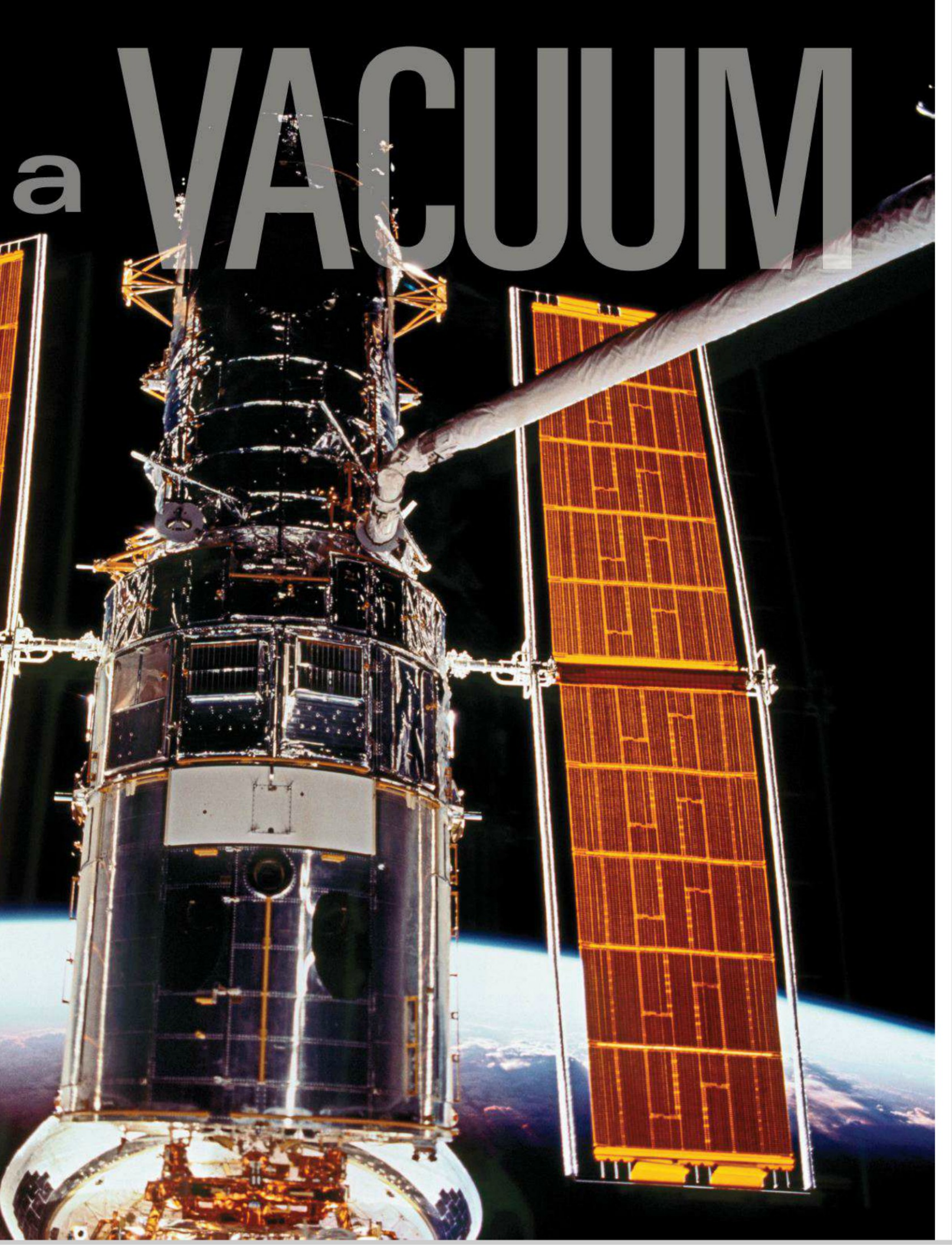
NASA launched its first two successful satellites designed to observe the stars in 1968 and 1972. These Orbiting Astronomical Observatory satellites produced a wealth of information, and support for a more powerful space telescope grew. When the agency launched the first space shuttle in 1981, its capacity to deliver and service large payloads made the space-telescope concept feasible.

NASA had selected a team of scientists in 1973 to establish the basic design of the first such telescope — Hubble — and its instruments. That telescope is part of NASA's Great Observatories series, a quartet of space-based telescopes that also includes the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope. These four and many others have since accumulated years of valuable data above Earth's blanket of air.

Ray Villard is the news chief, Outreach Programs Division, at the Space Telescope Science Institute in Baltimore, Maryland.

THE HUBBLE SPACE TELESCOPE, seen here emerging from the cargo bay of the space shuttle *Columbia* during a March 2002 servicing mission, remains at the forefront of research in large part because it has been upgraded five times. NASA





a VACUUM

43.5

Hubble's
length in feet
(13.3 meters)**Hubble Space Telescope****WEBSITE:** <http://hubblesite.org>**WAVELENGTHS:** visible, infrared, ultraviolet**MAIN INSTRUMENTS:**

- Wide Field Camera 3
- Advanced Camera for Surveys
- Cosmic Origins Spectrograph
- Space Telescope Imaging Spectrograph



ASTRONAUTS STORY MUSGRAVE (anchored on the shuttle's robot arm) and Jeffrey Hoffman (in the payload bay) work on Hubble during its initial servicing mission in December 1993. NASA

Hubble paves the way



A REFURBISHED HUBBLE sets its eye to the cosmos once again after receiving the Advanced Camera for Surveys and other upgrades in March 2002. NASA

The Hubble Space Telescope, a joint mission between NASA and the European Space Agency (ESA), is the largest ultraviolet, optical, and near-infrared observatory ever placed into space. The flagship of NASA's Great Observatory Program, Hubble has racked up more than a million observations and 10,000 science papers since its launch into low Earth orbit in 1990.

Originally christened the Large Space Telescope, the observatory was downsized from a 3-meter to a 2.4-meter aperture by a budget-conscious Congress in the 1970s.

NASA named the telescope after American astronomer Edwin Powell Hubble in the early 1980s.

Following the scope's launch, astronomers discovered that its ultra-smooth mirror had the wrong curvature. However, the mirror fabrication records allowed scientists to come up with an optical correction for Hubble — essentially fitting it with a contact lens — that allowed the telescope to perform to its original specifications.

Because Hubble is a key component to many astrophysics programs, NASA sent five space shuttle missions from 1993 to

100,000

The number of orbits logged
by the Hubble Space
Telescope as of
August 11, 2008



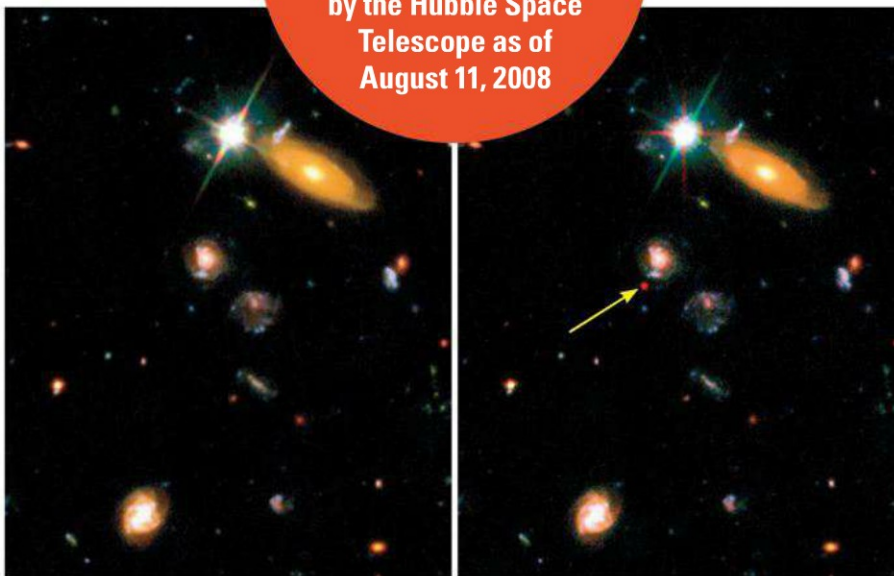
BARRED SPIRAL GALAXY NGC 1300 in Eridanus features a tapestry of bright star clusters, dark dust, and reddish hydrogen clouds. NASA/ESA/HUBBLE HERITAGE TEAM (STScI/AURA)

2009 to repair the telescope and upgrade it with ever more powerful instruments. These actions ensured an ongoing program of cutting-edge science.

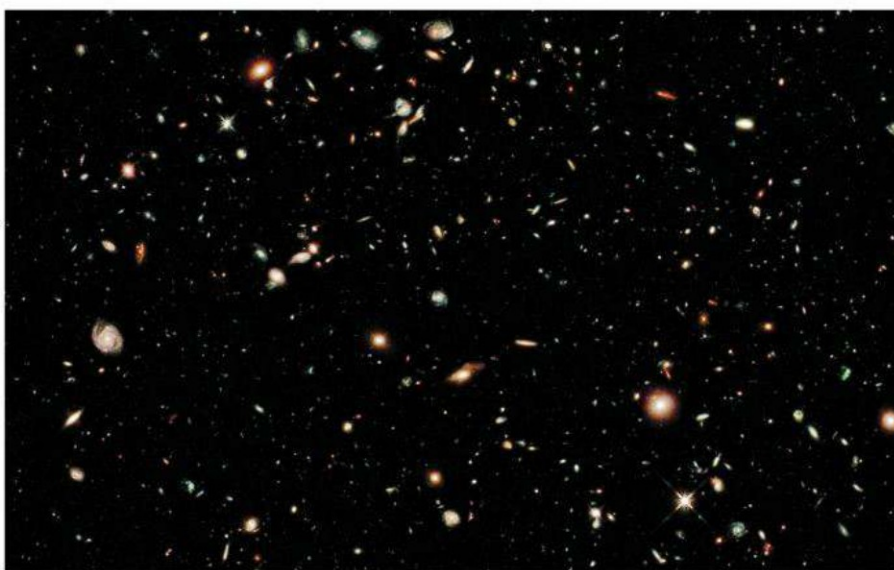
With a suite of state-of-the-art science instruments, Hubble now works at the apex of its scientific capability. The telescope has two multiwavelength cameras, an ultraviolet spectrometer (a device that divides light into its characteristic wavelengths and determines the chemical composition of an object), and an imaging spectrometer. Its fine-guidance sensors for aiming the telescope also conduct precision astrometry.

Hubble's major accomplishments include the discovery of supermassive black holes; providing a close-up look at a comet collision with Jupiter; the detection of protoplanetary disks; finding organic compounds in exoplanet atmospheres; precisely measuring the expansion rate of the universe; co-discovering dark energy; and tracing galaxy evolution as part of the Hubble Ultra Deep Field survey.

The telescope should remain operational through the end of the decade if no major malfunctions occur. Because NASA has canceled the Space Shuttle Program, the agency has no plans for further servicing missions. ☛



THE HUBBLE SPACE TELESCOPE played a critical role in the discovery of dark energy. Studies of distant supernovae (such as SN 2002dd, which appears as a red dot at right but not in an earlier shot at left) proved that cosmic expansion is accelerating. NASA/J. BLAKESLEE (JHU)



DISTANT GALAXIES more than 13 billion light-years away populate this near-infrared view from Hubble taken in 2009. NASA/ESA/G. ILLINGWORTH AND R. BOUWENS (UCO/LICK OBSERVATORY)/HUDF09 TEAM



THE STELLAR NURSERY known as the Eta Carinae Nebula (NGC 3372) contains stars forming from clouds of gas and dust. NASA/ESA/N. SMITH (UC, BERKELEY)/HUBBLE HERITAGE TEAM (STScI/AURA)

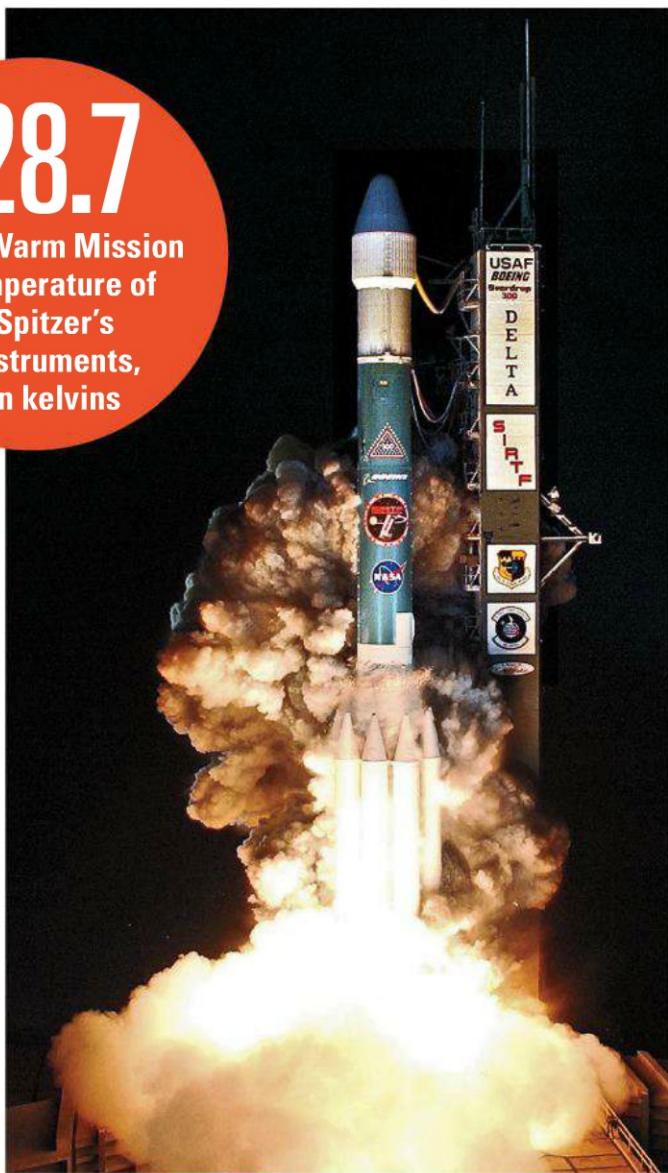


THE BUG NEBULA (NGC 6302) formed when a Sun-like star puffed off its outer layers as it ran out of nuclear fuel near the end of its life. NASA/ESA/HUBBLE SM4 ERO TEAM

Spitzer sees the invisible

28.7

The Warm Mission temperature of Spitzer's instruments, in kelvins



THE SPITZER SPACE TELESCOPE launches from Cape Canaveral, Florida, on August 25, 2003. This Delta II rocket delivered the observatory to an unusual Sun-centered orbit that trails Earth and slowly drifts away from our planet. NASA/KSC

NASA's Spitzer Space Telescope detects infrared radiation between 3 and 180 microns. This window on the universe allows astronomers to peer into regions hidden from optical telescopes: dusty stellar nurseries, the centers of galaxies, newly forming planetary systems, brown dwarfs, extrasolar planets, and giant molecular clouds that are spawning new rounds of stars.

The heart of the observatory is the Cryogenic Telescope Assembly, which contains a 33-inch-diameter (85 centimeters) mirror that engineers originally chilled to -450° Fahrenheit (-268° Celsius) with an onboard tank containing 95 gallons (360 liters) of liquid helium. Spitzer contains three instruments that, when chilled to such cryogenic temperatures, allow it to perform infrared imaging, photometry, and spectroscopy.

The telescope became the first instrument to directly capture radiation from a class of extrasolar planets called "hot Jupiters" — giant planets that orbit close to their parent stars. Astronomers also measured one of these objects' atmospheric temperature, which enabled them to construct the first thermal map of an extrasolar planet. In another case, Spitzer imaged the dust that provided telltale evidence of a high-speed collision between two planets orbiting a young star.

Astronomers allotted Spitzer 400 hours of observing time to map our Milky Way. Optical telescopes can see only about 9 percent of our galactic system, but Spitzer's infrared capability allowed it to peer through dust to the far side of the galaxy. The scope revealed a more substantial bar structure of stars and gas across the galactic core than astronomers previously realized.

Launched in 2003, engineers planned a minimum of a 2.5-year lifetime for Spitzer. In May 2009, the last of the liquid helium necessary to cool the telescope evaporated. However, even at a higher temperature, the two shortest-wavelength instruments still operate with no change in sensitivity. So NASA inaugurated the Spitzer Warm Mission, which should extend the observatory's lifetime an additional 5.5 years. 🌌

Spitzer Space Telescope

WEBSITE:

www.spitzer.caltech.edu

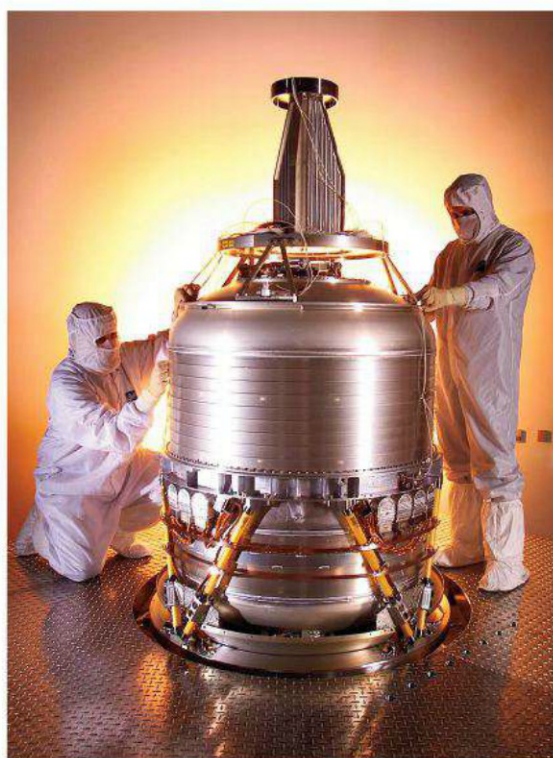
WAVELENGTHS: 3 to 180 microns (infrared)

MAIN INSTRUMENTS:

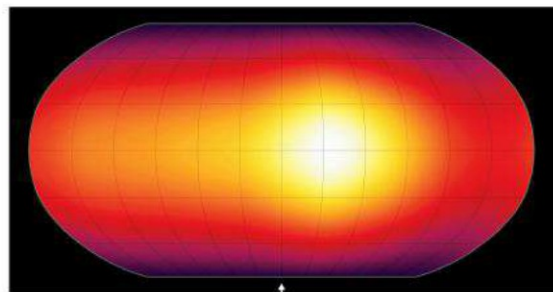
- Infrared Array Camera
- Infrared Spectrograph
- Multiband Imaging Photometer



THE MILKY WAY in Norma is full of stars and glowing gas in this Spitzer infrared view. The space telescope's observations of our galaxy helped show that it is a barred spiral. NASA/JPL-CALTECH/E. CHURCHWELL (UNIV. OF WISCONSIN)



THE HEART OF SPITZER is the Cryogenic Telescope Assembly (CTA), which kept the telescope and its instruments cooled to -450° Fahrenheit (-268° Celsius) from launch in 2003 until 2009. Here, technicians prepare the CTA for vibration testing. BALL AEROSPACE



SPITZER TOOK THE TEMPERATURE of HD 189733b, a "hot Jupiter" exoplanet. This map of the planet's cloud tops reveals a warm spot (bright yellow) on its "sunlit" side. NASA/JPL-CALTECH/H. KNUTSON (HARVARD-SMITHSONIAN CfA)

Chandra: X marks the spot



CASSIOPEIA A, a supernova remnant 11,000 light-years away, glows in this composite image from Chandra, Hubble, and Spitzer.

NASA/CXC/SAO; NASA/STScI; NASA/JPL-CALTECH

NASA's Chandra X-ray Observatory is the most powerful such spacecraft ever flown. Chandra's orbit — once every 64.2 hours — is an ellipse that places it 86,500 miles (139,200 kilometers) above Earth at its farthest point and 9,900 miles (16,000 km) at its closest. The telescope boasts a sensitivity 100 times greater than any previous X-ray telescope, and its images are 1,000 times sharper.

Chandra's launch occurred July 23, 1999, aboard the space shuttle *Columbia*. Scheduled for a 10-year mission, the observatory's lifetime may extend beyond 15 years. Originally called the Advanced X-Ray Astrophysics Facility, NASA renamed Chandra in honor of Indian-American physicist Subrahmanyan Chandrasekhar, who determined the maximum mass for white dwarfs.

Chandra's optics consist of four pairs of mirrors nested inside each other. X-ray photons ricochet down a 30-foot-long (9.1 m) telescope tube and converge onto electronic detectors that produce images and spectra of cosmic X-ray sources.

Scientists designed Chandra to detect emissions from the hottest regions of the universe. These include exploding stars, clusters of galaxies, and matter falling into black holes. But the observatory also has imaged the spectacular glowing remains of supernovae and taken spectra showing how elements have dispersed throughout the cosmos.

It also has studied the region around the supermassive black hole at the center of our Milky Way and traced the separation of dark matter from normal matter brought about by the collision of galaxies in clusters. ☛

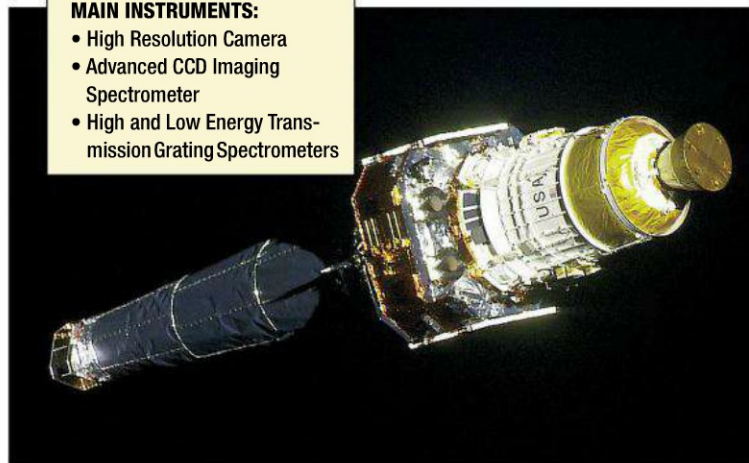
Chandra X-ray Observatory

WEBSITE: <http://chandra.si.edu>

WAVELENGTH: X-rays

MAIN INSTRUMENTS:

- High Resolution Camera
- Advanced CCD Imaging Spectrometer
- High and Low Energy Transmission Grating Spectrometers



THE CHANDRA X-RAY OBSERVATORY drifts slowly away from the space shuttle *Columbia* after deployment July 23, 1999. The inertial upper stage (with its cone-shaped nozzle at right) later fired to place the spacecraft into a much higher and more elongated orbit. NASA

FIRST
(Far-Infrared and
Sub-millimetre Telescope)
— The Herschel Space
Observatory's
original name

Herschel Space Observatory

WEBSITE: www.esa.int/herschel

WAVELENGTHS: 55 to 672 microns
(infrared to submillimeter)

MAIN INSTRUMENTS:

- Photoconductor Array Camera and Spectrometer
- Spectral and Photometric Imaging Receiver
- Heterodyne Instrument for the Far Infrared

THE COSMIC BUBBLE RCW 120, sculpted by intense ultraviolet light from a few massive stars at its center, glows in the infrared radiation Herschel sees. New stars form on the bubble's periphery as it expands into surrounding gas and dust. ESA/PACS/SPIRE/HOBYS CONSORTIA

Big, bold Herschel

ESA's Herschel Space Observatory is the largest infrared observatory ever flown. Engineers optimized its 3.5-meter mirror to detect far-infrared and submillimeter radiation between wavelengths of 55 and 672 microns. The telescope bridges the gap in the spectrum between what ground-based instruments can observe and what earlier infrared space telescopes such as Spitzer gleaned.

The mirror focuses infrared light into a cryostat — a giant thermos flask — that sits under the mirror and cools the instruments to below -456°F (-271°C), near absolute zero. A sunshade not only shields the primary mirror from our star's heat but also carries solar cells that provide the power required to operate the telescope and its instruments.

The observatory excels at imaging, high-resolution spectroscopy, and

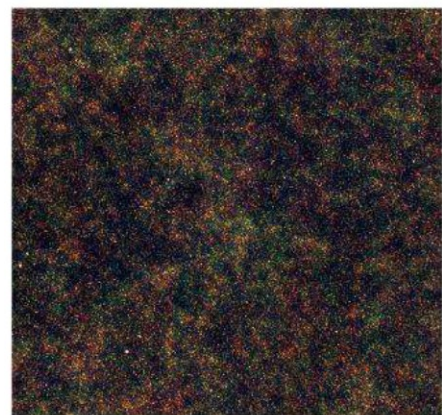
photometry (determining the brightness of celestial objects). Because it collects far-infrared data, Herschel's instruments can penetrate the gas and dust clouds that hide objects from optical telescopes. This window on the universe allows Herschel to see the coldest and dustiest objects in space: cool cocoons where stars form and dust-enshrouded galaxies. It also can identify water molecules.

Scientists named the telescope after the 18th-century German-born English astronomer Sir William Herschel. It launched on an Ariane 5 heavy-lift booster in May 2009 together with ESA's Planck spacecraft. The observatory is orbiting Earth-Sun Lagrangian point 2, which is a gravitationally stable location for parking space telescopes 930,000 miles (1.5 million km) from Earth.

Currently, Herschel is conducting a survey of the formation and evolution of



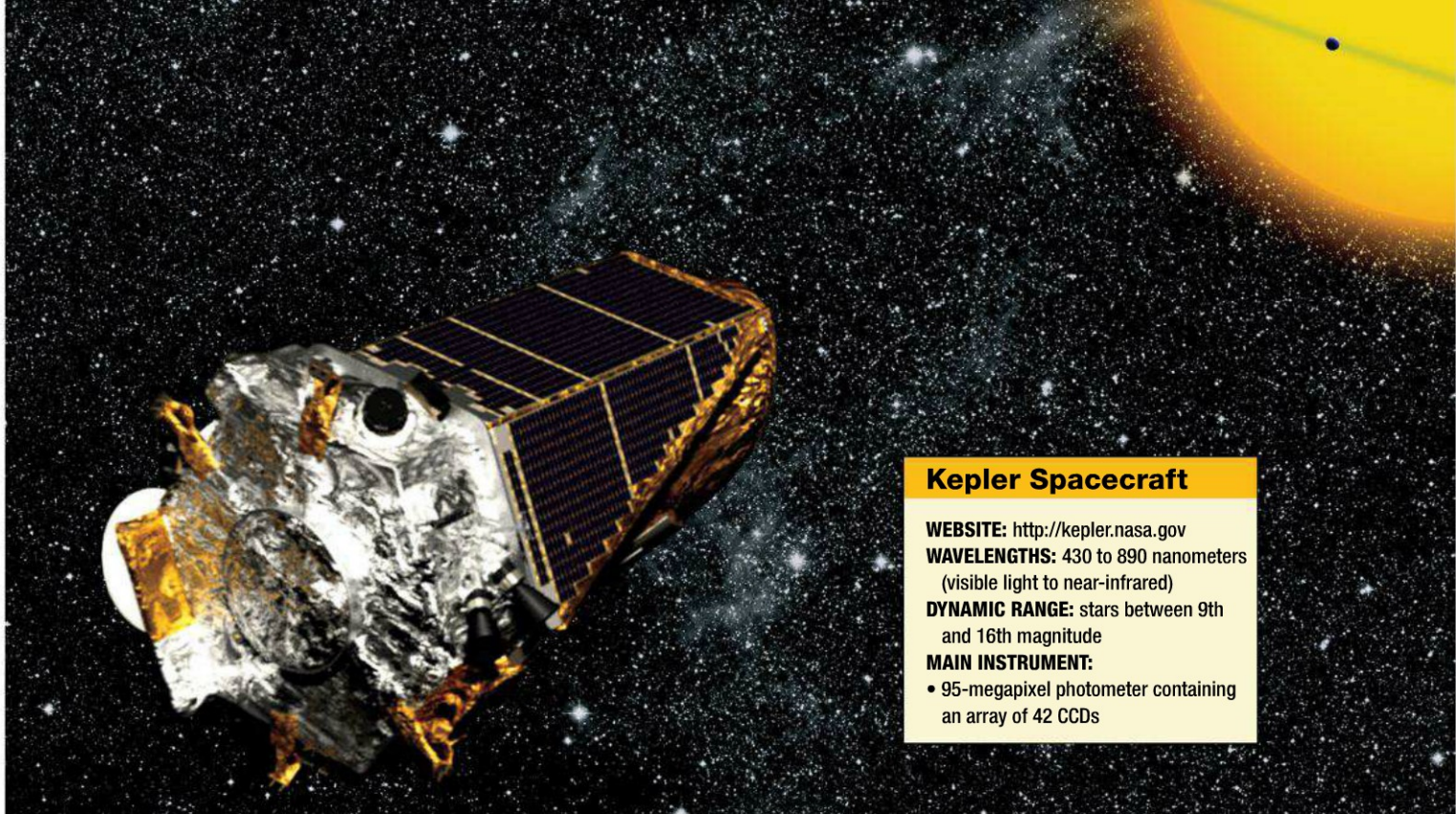
THE HERSCHEL SPACE OBSERVATORY and Planck mission launch together May 14, 2009, from French Guiana.



GALAXIES GALORE fill this Herschel image of the distant universe. Each of the many thousands of dots are abnormally bright at the infrared wavelengths Herschel records. This region of space lies in the constellation Ursa Major the Great Bear.

elliptical galaxies and the central bulges of spiral galaxies during the first several billion years of the universe's history. Astronomers are using the telescope to target these objects in order to find clues to the physical processes and energy-generating mechanisms in galaxies.

Herschel is designed for a 3-year mission. Like Spitzer, the scope's primary function will end when the helium used to cool the telescope evaporates sometime between late 2012 and spring 2013. ☼



Kepler Spacecraft

WEBSITE: <http://kepler.nasa.gov>

WAVELENGTHS: 430 to 890 nanometers
(visible light to near-infrared)

DYNAMIC RANGE: stars between 9th
and 16th magnitude

MAIN INSTRUMENT:

- 95-megapixel photometer containing an array of 42 CCDs

NASA'S KEPLER SPACECRAFT monitors more than 100,000 stars in Cygnus and Lyra, searching for a telltale drop in brightness that signals an orbiting planet. In this artist's conception, an Earth-like world passes in front of a Sun-like star. NASA/KEPLER MISSION/WENDY STENZEL

Kepler looks for other Earths

61

The number of
confirmed planet
discoveries Kepler
has made as of
March 1, 2012

NASA's Kepler spacecraft seeks out Earth-like planets orbiting other stars. Kepler can't directly observe planets but instead measures the slight dimming of their host stars as the objects pass in front of them.

Kepler's 0.95-meter mirror has a field of view that covers 105 square degrees within the constellations Cygnus the Swan and Lyra the Harp. It continuously and simultaneously monitors the light of more than 100,000 stars brighter than 16th magnitude. A star of that brightness is about 1,000 times fainter than the human eye can detect from a dark site.

To detect an Earth-sized planet, Kepler's photometer — the most sensitive light-meter ever built — must sense a drop in brightness of only 0.01 of 1 percent. This is akin to measuring the dip in a car headlight's output when a fruit fly moves in front of it. Such precision is possible only with a space-based observatory.

The heart of Kepler, a 95-megapixel photometer, is the largest detector NASA has ever launched into space. It has 42 charge-coupled devices (CCDs), and each

has a chip with 2.25 million pixels. The unit operates nonstop, and a computer reads its CCD array every six seconds.

Scientists apply this massive data collection to monitoring starquakes — acoustic waves generated deep inside a star that ripple across its surface, altering its brightness. The nature of the ripples allow astronomers to calculate a star's mass, age, and chemical composition.

As of March 1, 2012, Kepler had discovered 2,321 exoplanet candidates, making it the most prolific planet-hunter telescope ever built. And on December 5,

2011, mission scientists announced the confirmation of the first planet discovery in its Sun-like star's habitable zone (the region around a star where an Earth-like planet could maintain liquid water on its surface). Scientists designated the object Kepler-22b. It lies 600 light-years away. While this planet is larger than Earth, its orbit of 290 days resembles the orbital period of our world.

Confirming a planet requires seeing transits at regular intervals as the planet orbits its star as well as follow-up observations with ground-based telescopes and Spitzer. The brightness change indicates the planet's size, and the time between transits yields the planet's orbital period.

Based on Kepler's findings to date, researchers estimate that at least 30,000 habitable planets exist within 1,000 light-years of Earth. They also estimate that at least 500 million planets populate the Milky Way. Kepler, launched March 6, 2009, has a planned lifetime of 3.5 years — the minimum estimated time required for finding Earth-like planets. ☼



SAPPHIRE LENSES cover the 42 CCDs (two in each of the larger modules) of Kepler's 95-megapixel camera. NASA/KEPLER MISSION

Small but mighty CoRoT

The CONvection ROTation and planetary Transits (CoRoT) space telescope searches for Earth-like extrasolar planets and performs asteroseismology by measuring solar-like oscillations, or starquakes, in stars.

The spacecraft entered orbit in 2006. Depending on Earth's seasonal tilt (the spacecraft keeps the same orientation with respect to our planet), CoRoT targets an area in the constellation Serpens, the galactic center, or a region in Monoceros that lies in the opposite direction of the galactic center.

The heart of the small observatory is a 27-centimeter telescope and a two-part camera that also has spectroscopic capability. CoRoT can detect planets some several times larger than Earth as they slightly dim the light of their parent star during transits. The scope also studies stellar vibrations to determine stars' internal structure, age, and composition.

Since its launch, CoRoT has detected several hundred candidate planet-hosting stars. To date, ground-based follow-up observations have confirmed 26 exoplanets in orbit around these stars. The majority of confirmed planets are hot Jupiters, but CoRoT also has identified rocky "super-Earth" planets, some within the habitable zones of their stars. On the other hand, one super-Earth — CoRoT-Exo-7b — lies so close to its star that it could only have oceans of molten magma.

The French National Space Agency, CNES, leads the mission in conjunction with ESA and other international partners. Engineers expect CoRoT to continue operating to 2013. 🌌



CONvection ROTation and planetary Transits (CoRoT)

WEBSITE:

<http://smc.cnes.fr/COROT>

WAVELENGTH: Visible light

MAIN INSTRUMENTS:

- 27-centimeter telescope
- Two-part, four-CCD camera

CoRoT — the CONvection ROTation and planetary Transits telescope — undergoes electromagnetic testing before its 2006 launch. The scope detects planets and studies stellar vibrations. CNES



THE RADIO GALAXY CENTAURUS A glows some 10 times brighter at gamma-ray energies (purple) as imaged by NASA's Fermi Gamma-ray Space Telescope. NASA/DOE/FERMI LAT COLLABORATION, CAPELLA OBSERVATORY

Fermi studies the highest energies

NASA's Fermi Gamma-ray Space Telescope is a survey

instrument that scans the entire sky every three hours to document high-energy events occurring in the universe.

Gamma rays are the most energetic form of radiation. If we could see the invisible gamma-ray sky, it would glitter like a stadium full of camera flashes going off. These extraordinary bursts of energy come from some of the most violent objects in the universe: super-massive black-hole systems, pulsars, and supernovae.

To date, the telescope has discovered 1,873 gamma-ray sources. "More than half of the sources are active galaxies, whose massive black holes are

responsible for the gamma-ray emissions," says Gino Tosti, an astrophysicist at the University of Perugia in Italy.

These relatively steady sources are in addition to the numerous transient events that Fermi detects. Those include gamma-ray bursts in distant galaxies and solar flares.

A third of the Fermi catalog contains sources that scientists cannot associate with any visible celestial object. Surprisingly, gamma-ray sources identified include several supernova remnants, including the Crab Nebula (M1). The telescope also discovered the first gamma-ray pulsar in a globular cluster.

In addition, Fermi detected two gamma-ray and X-ray bubbles extending 25,000 light-years above and below the center of



FERMI — NASA's latest gamma-ray observatory — launches from Cape Canaveral, Florida, on June 11, 2008. This rocket placed Fermi in a 340-mile-high (550 kilometers) orbit. NASA/JERRY CANNON, ROBERT MURRAY

Fermi Gamma-ray Space Telescope

WEBSITE: www.nasa.gov/fermi

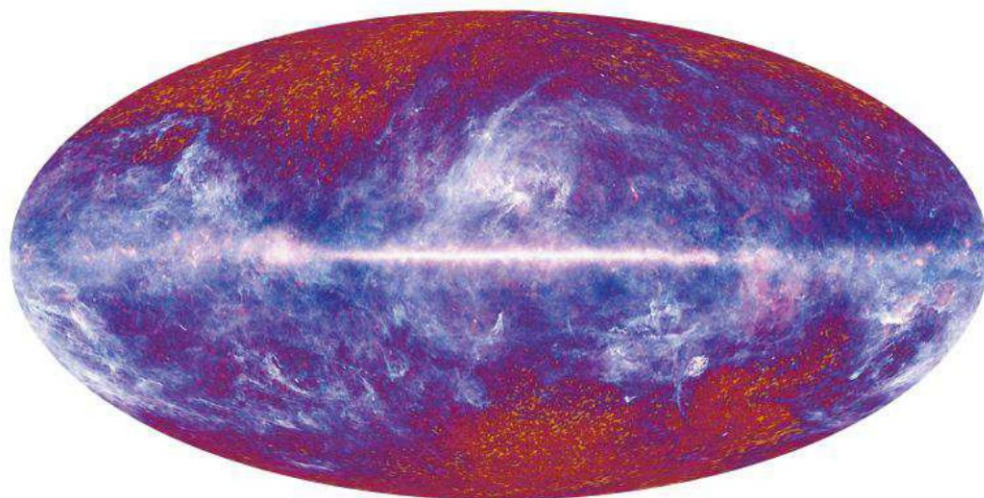
WAVELENGTH: Gamma rays

MAIN INSTRUMENTS:

- Large Area Telescope
- Gamma-ray Burst Monitor

the Milky Way. The structures' shape and emissions suggest that they formed as a result of a large and relatively rapid energy release, the source of which remains a mystery. One possibility includes a past particle jet from the supermassive black hole at the galactic center. A burst of star formation also may have created the bubbles.

Fermi represents a partnership between NASA and the U.S. Department of Energy. Originally called the Gamma-ray Large Area Space Telescope, researchers renamed it after Italian-born American physicist Enrico Fermi, who pioneered the commercial use of nuclear energy. Launched into low Earth orbit June 11, 2008, the mission has a planned five-year lifetime with a possible extension to 10 years. ☛



PLANCK'S FIRST ALL-SKY SURVEY shows microwaves from the Milky Way (the horizontal band) and the mottled cosmic microwave background at top and bottom. ESA/LFI & HFI CONSORTIA

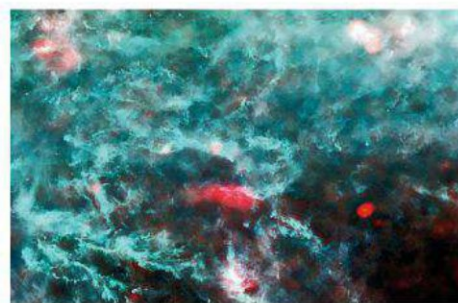
Planck — back to the beginning

Planck is ESA's first space mission to study the primeval radiation from the Big Bang, called the cosmic microwave background (CMB). The mission follows the spectacular accomplishments of NASA's COsmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP).

In 1992, COBE first mapped thermal mottling in the CMB, which revealed the seeds of galaxy structure in the early universe. In 2003, WMAP resolved finer structure in the primeval universe and definitively determined that the universe was 13.7 $\pm$ 0.2 billion years old. WMAP showed that space is essentially flat, and it measured the percentages of dark energy and dark matter.

What, then, is left for Planck to do? This microwave observatory is measuring temperature variations across the CMB with much better resolution and in a different wavelength range. This will yield the most accurate map yet of the CMB.

Planck observations have produced a catalog of more than 15,000 foreground objects like galaxies, stars,



THE CONSTELLATION PERSEUS glows at microwave wavelengths in this Planck view of a star-forming region. ESA/LFI & HFI CONSORTIA

gas, and dust (which distort radiation left over from the Big Bang) that will become targets for future study. These include 189 gigantic clusters of galaxies (including 20 never seen before) and a previously undetected high-density molecular gas found clinging to the edges of giant molecular clouds in the Milky Way.

The Planck telescope and instruments are mounted atop an octagonal service module. A baffle surrounds the telescope and instruments to prevent stray light from the Sun and Moon from contaminating the feeble glow of the microwave radiation. The passively cooled telescope radiates instrument heat into space to provide for a background temperature of -387°F (-233°C).

The mission's name honors German physicist Max Planck, whose work on the behavior of radiation won him the 1918 Nobel Prize in physics. Planck launched in tandem with ESA's Herschel Space Observatory. It operates in a highly elliptical orbit that takes it near Lagrangian point 2. ☛

Planck

WEBSITE:

www.esa.int/planck

WAVELENGTHS: 1 centimeter to 0.33 millimeter (microwaves)

MAIN INSTRUMENTS:

- Low and High Frequency Instruments



Swift Gamma-Ray Burst Mission

WEBSITE: www.nasa.gov/swift

WAVELENGTHS: Gamma rays, X-rays, ultraviolet, and visible

MAIN INSTRUMENTS:

- X-ray Telescope
- Ultraviolet/Optical Telescope
- Burst Alert Telescope

SWIFT STUDIES GAMMA-RAY BURSTS (GRBs): These roughly once-a-day blasts release copious amounts of high-energy radiation in anywhere from a tiny fraction of a second to several minutes. In this artist's concept, Swift views an especially powerful GRB. SPECTRUM ASTRO

Swift — like a bird in flight



SWIFT SETS OFF to understand gamma-ray bursts November 20, 2004. NASA/KSC

Launched into Earth orbit in 2004, Swift is a multiwavelength observatory and the central piece in the Swift Gamma-Ray Burst Mission dedicated to studying gamma-ray bursts (GRBs, flashes of gamma rays associated with energetic explosions). Three onboard instruments work together to observe GRBs and their afterglows in the gamma-ray, X-ray, and the combined ultraviolet (UV) and optical regions of the spectrum.

Swift is determining the origin of GRBs and finding different types in terms of duration and energy output. It has carried out the most comprehensive study of GRB afterglows to date, cataloging more than 715 sources as of December 2011.

Within seconds of detecting a burst, the spacecraft rapidly and autonomously re-points itself to aim its X-ray and UV/optical telescopes at the burst to pinpoint its location. It then relays the position to

the ground for follow-up by a network of observers at various telescopes.

In 2009, Swift detected the farthest GRB to date at approximately 13.14 billion light-years. The universe was only 520 million years old when it occurred. The previous year, Swift detected a burst of gamma rays that was among the brightest such events ever witnessed. At 7.5 billion light-years, Swift established a new record for the farthest object visible to the naked eye, albeit briefly.

Unlike the names of most NASA satellites, Swift is not an acronym, and the agency did not name the spacecraft after any scientist. Instead, researchers named Swift for the bird that can change its flight path quickly.

A consortium from the United States, England, and Italy developed Swift. The truck-sized observatory had a nominal lifetime of seven years, but it's operating in its eighth year as you read this. 🐦

XMM-Newton — lots of options

XMM-Newton

WEBSITE: <http://sci.esa.int/xmmnewton>

WAVELENGTHS: X-rays

MAIN INSTRUMENTS:

- European Photon Imaging Camera
- Reflection Grating Spectrometers
- Optical Monitor

ESA's X-ray Multi-Mirror Mission-Newton (XMM-Newton) entered into an elliptical Earth orbit in 1999. The 33-foot-long (10m) satellite contains three X-ray cameras, two spectrometers, and an ultraviolet/optical camera.

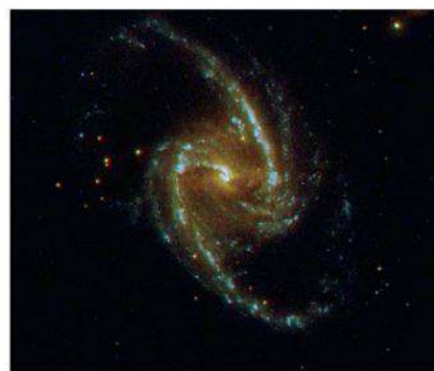
The observatory's orbit carries it as far as 71,000 miles (114,000km) from Earth. This allows for long exposures uncontaminated by radiation from Earth's Van Allen belts (regions of charged particles around Earth held in place by our planet's magnetic field). XMM-Newton has worked in parallel with NASA's Chandra to combine that telescope's imaging with XMM-Newton's spectral resolution.

The spacecraft monitors X-ray emissions from solar system objects, star-

forming regions, galaxy clusters, and the environment around black holes. Its observations have offered new insights into the way in which supermassive black holes grow and drive the evolution of the most massive galaxies. It has tracked the dispersal of heavy chemical elements by exploding stars and measured powerful magnetic activity coming from young Sun-like stars.

XMM-Newton has discovered that Mars has a vastly more extended atmosphere than previously thought and that icy comets from the outer solar system give off X-rays. And, astonishingly, it pinpointed a 200-foot-diameter (60m) hot spot on a neutron star 552 light-years away. Engineers expect the telescope to operate beyond 2014. ☛

XMM-NEWTON DISCOVERED a new X-ray pulsar (the bright blue dot at right) in our neighboring galaxy the Small Magellanic Cloud. NASA/CXC/UNIV. OF POTSDAM/L. OSKINOVA, ET AL.



BARRED SPIRAL GALAXY NGC 1365 in Fornax shows many regions of active star formation in this ultraviolet view from XMM-Newton. MARCO IACOBELLI (XMM-NEWTON SOC)/ESA



How to see Hubble

Although the observatories described in this article are beyond the reach of human hands, human eyes can spot sunlight reflected by the Hubble Space Telescope. Under favorable conditions, the spacecraft's 90-minute orbit carries it to a position where our star illuminates it while you experience twilight or night. Occasionally, Hubble shines as brightly as a 1st-magnitude star.

To find out when the observatory will be

visible above you, visit the website of Heavens Above at www.heavens-above.com. Enter your longitude and latitude. Then click on the "HST" link, and the website will spit out predictions for viewing Hubble during the next 10 days. Heavens Above also gives the visibility of other satellites, including the International Space Station.

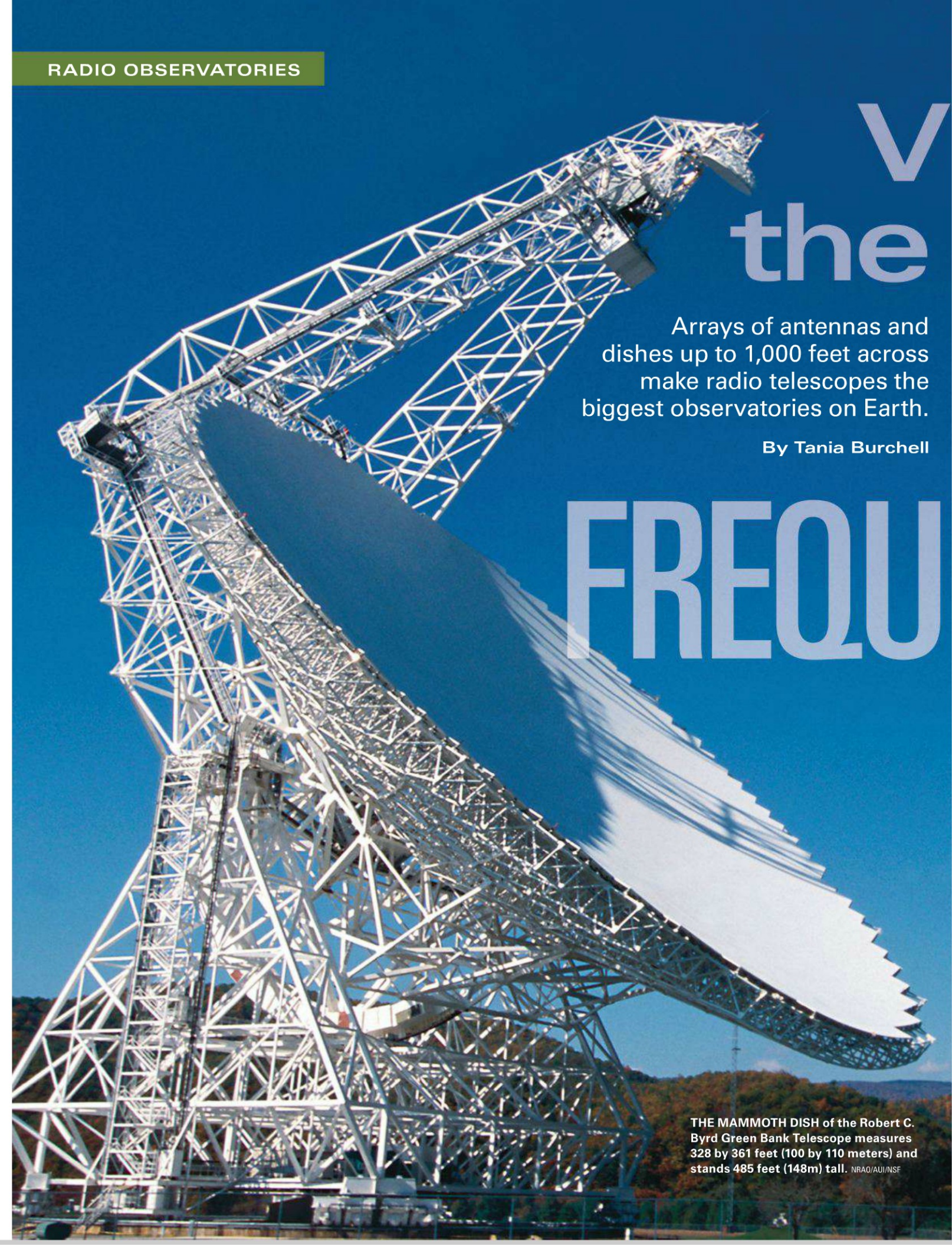
We've only just begun

Space telescopes are here to stay. The sheer amount of data astronomers have received from any of the spacecraft described in this story will keep them busy for decades. And even now, engineers are planning the next generation of these incredible observatories.

Currently, the most exciting upcoming project in astronomy is NASA's James Webb Space Telescope, now under construction and scheduled to launch in 2018. That instrument, optimized to collect infrared radiation, will search for the first galaxies, peer through dust clouds at forming planetary systems, and possibly unravel the secret behind the Big Bang itself.

Early astronomers peering through earthbound telescopes could scarcely have imagined that a large percentage of 21st-century astronomy would occur above our layer of life-giving air — in the very region we call space. ☛

6.5
The diameter, in meters,
of the James Webb Space
Telescope's primary mirror
(21.3 feet)



RADIO OBSERVATORIES

V
the

Arrays of antennas and
dishes up to 1,000 feet across
make radio telescopes the
biggest observatories on Earth.

By Tania Burchell

FREQU

THE MAMMOTH DISH of the Robert C. Byrd Green Bank Telescope measures 328 by 361 feet (100 by 110 meters) and stands 485 feet (148m) tall. NRAO/AUI/NSF

iewing sky at RADIO ENCIES

T

he pursuit of radio astronomy is a quest for cosmic whispers. By the time radio telescopes collect them, the universe's broadcasts are but a billionth of a billionth the power of a cellphone ping. To have any hope of detecting the cries of infant and dying stars, the subtle shimmying of molecules in gaseous clouds, or the faint ignitions of the early universe, radio astronomers must invent new technologies, plug them into huge sophisticated telescopes, and safely plant them in the most remote and, often, most extreme locations on Earth.

NRAO

Green Bank, West Virginia

A rollercoaster of mountain switchbacks dominates the journey into the womb of American radio astronomy: the National Radio Astronomy Observatory in Green Bank, West Virginia. Embraced by the natural fortress of the Allegheny Mountains, Green Bank was a cozy timber town when it was chosen as the quiet birthplace of the National Radio Astronomy Observatory (NRAO) in 1956.

Enclosed in 13,000 square miles (33,700 square kilometers) of federally mandated radio-quiet zoning, Green Bank's forests are free from cell towers. However, nine research antennas and three historic ones poke out among the conifers, and visitors can pedal freely around them on bikes or take a guided bus tour that visits most of them.

The first large dish in view is the 85-foot (26 meters) Tatel, an Erector Set-like radio telescope skulking behind its old control building. In 1960, under the command of astronomer Frank Drake, this telescope was the first in the world used for the Search for Extraterrestrial Intelligence (SETI) research.

Across from the Tatel is the U.S. Naval Observatory's former 20-meter geodetic telescope now being resurrected as a robotic instrument for citizen scientists.

The road bends around "the beautiful brute," a 140-foot (43m) aperture radio telescope completed in 1965 and reigning still as the largest equatorially mounted telescope in the world. Its polar shaft is topped with a 17.5-foot (5.3m), 150-ton nickel-steel bearing, the biggest ever cast. This scope discovered several organic molecules in space, spearheading the field of astrochemistry.

With a later reconfiguration from prime focus to a Cassegrain feed, and the addition of new receivers and a computer control system, the renamed "43-meter" now studies Earth's ionosphere and hunts for cosmic radio bursts.

At the bottom of the valley lurks the world's largest fully steerable telescope, the Robert C. Byrd Green Bank Telescope (GBT). Visitors disembark to gawk up at this colossal and unique feat of engineering. The use of digital cameras is forbidden so near a working radio telescope, but, frankly, any camera struggles to capture the entire view.

The GBT is a 328-foot by 361-foot (100m by 110m) section of a virtual 682-foot (208m) parabola, with a feed arm climbing the side. This 485-foot-high (148m) behemoth boasts more than 2 acres of collecting area, coated in a bright white, infrared-reflecting paint that makes it painful to look at in

Tania Burchell is the science writer at the National Radio Astronomy Observatory headquarters in Charlottesville, Virginia, and also pens online as RadioAstroGal. Burchell unabashedly hugged all but one of the telescopes in this article.

NRAO, Green Bank**LOCATION:** Green Bank, West Virginia**WEBSITE:** <https://science.nrao.edu/facilities/gbt>**VISITORS WELCOME:** Varies by season**TOURS:** When science center is open, tours every hour 9 A.M.–6 P.M. Memorial Day–October; 11 A.M., 1 P.M., and 3 P.M. November–Memorial Day**TELESCOPES:**

- 100-meter Robert C. Byrd Green Bank Telescope
- 43-meter Telescope
- 45-foot Telescope

THE ALLEGHENY MOUNTAINS surrounding Green Bank, West Virginia, shield the National Radio Astronomy Observatory and its telescopes (including the 140-foot [43 meters] dish seen here) from outside radio interference. NRAO/AUI/NSF

sunshine. For this huge dish to maintain its shape to within the thickness of a few sheets of paper, 2,209 robotic pistons responsively adjust the corners of each of its 2,004 aluminum surface panels.

Completed in 2000, this “Great Big Telescope” enjoys unblocked views of 85 percent of the celestial sphere. The axis of its altitude gear is supported above a sturdy-wheeled carriage that smoothly spins its 16-million-pound (7 million kilograms) burden, making it the largest moving man-made structure on Earth.

Thanks to the Gregorian secondary’s removable prime-

focus receiver and a rotating turret packed with eight more below, the GBT can collect frequencies from 290 megahertz to 116 gigahertz and, in a single day, can examine the subsurfaces of the moons of Jupiter, discover pulsars, map passing asteroids, and track hydrogen clouds to clock the spins of their host galaxies, including our Milky Way.

The large, modern Green Bank Science Center offers visitors a café, restrooms, a well-stocked gift shop, and a hands-on radio astronomy learning center. Tip for chocolate lovers: Ask for a Bill Saxton cone. ☺



EACH ANTENNA of the Very Large Array measures 82 feet (25 meters) across and weighs 230 tons. The 27 antennas move along railroad tracks, which allows array operators to maneuver them into four different configurations. BILL SAXTON (NRAO/AUI/NSF)

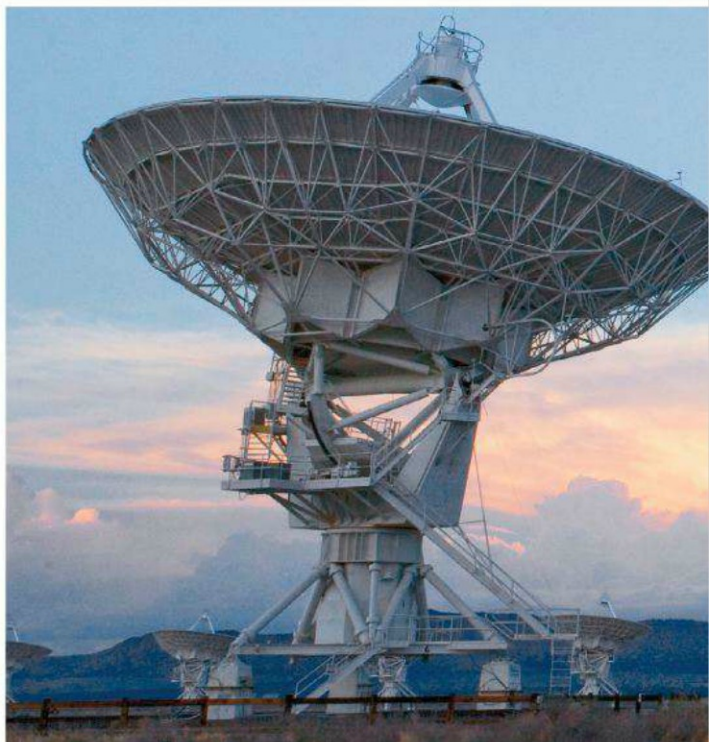
Very Large Array

Plains of San Agustin, New Mexico

For eyes dazzled by the technicolors of city living, the New Mexico landscape is at first a dreary desert of dull. A few thousand shrubs into the 50-mile (80 kilometers) drive between Socorro and the Very Large Array (VLA), however, the human brain hones in on the subtle spectrum of beiges daubed with sage, highlighted here and there by an energetic golden antelope.

Past the charming old stockyard town of Magdalena, an ancient dry lakebed of the Plains of San Agustin forms a mountain-rimmed fortress, a natural radio-quiet sanctuary for the most versatile and powerful radio telescope in the world, the VLA.

Since 1981, more than 40 miles (65km) of recycled train tracks have traced out three 13-mile-long (21km)



arms eponymously called the Wye because of its Y shape. Large red antenna transporters slowly haul and deposit 230-ton VLA telescopes to new locations along these tracks several times a year.

Depending on the configuration, all 27 working dishes of the VLA may be within sight of the visitors center or separated so widely along the Wye that many are but lonely sentinels far out on the plains. At those latter times, the resolution of the VLA's highest frequency images is 0.04 arcsecond — that's more than 10 times the resolution of the Hubble Space Telescope.

The National Radio Astronomy Observatory is now enhancing the VLA telescopes, fitting them with a suite of upgraded cryogenic receivers that receive frequencies from 1.0 to 50 gigahertz. Using laser timing, fiber optics, the sweeping sky effect of Earth's spin, and a supercomputer working at 16 quadrillion operations a second, the 25-meter telescopes of the VLA will become one giant enhanced radio eye up to 22 miles (36km) across. This Expanded Very Large Array, as it will be known, should be completed in late 2012.

The visitors center has a theater, exhibits, and a full gift shop. A souvenir map details a self-guided walking tour that leads directly to one of the active telescopes. The wooden safety corral does not diminish the extraordinary sensation of looking up at one of these 94-foot-tall (29m) giants.

A side tour steers visitors to the enormous Antenna Assembly Building (AAB), almost always occupied by a telescope in need of repair, with a 28th (spare) telescope replacing it in the array. With lucky timing, visitors can watch the transporters swap the AAB's enormous occupants. Tip: For the best chance of a visit while transporters are rearranging the array, pick a date outside the "Observing Periods" listed in the VLA configuration calendar at <https://science.nrao.edu/facilities/evla/index>.

The VLA grounds are open to visitors every day from 8:30 A.M. Mountain time until dusk, with exclusive behind-the-scenes tours on the first Saturday of every month. 📡



THE VERY LARGE ARRAY comprises 27 antennas spread across New Mexico's Plains of San Agustin. In the so-called D configuration seen here, the total array spans 0.6 mile (1 kilometer). NRAO/AUI/NSF



THE MAJOR RADIO OBSERVATORIES of the United States spread across the country from the plains of New Mexico to the mountains of West Virginia and the island of Puerto Rico. A fourth national site, ALMA, resides in Chile.

CLOUDY WEATHER doesn't affect the Very Large Array (VLA), or most other radio telescopes for that matter. Radio waves from space pass through clouds as if they weren't there, allowing the VLA to operate 24 hours a day, seven days a week. NRAO/AUI/NSF

Very Large Array

LOCATION: Plains of San Agustin, New Mexico

WEBSITE: www.vla.nrao.edu

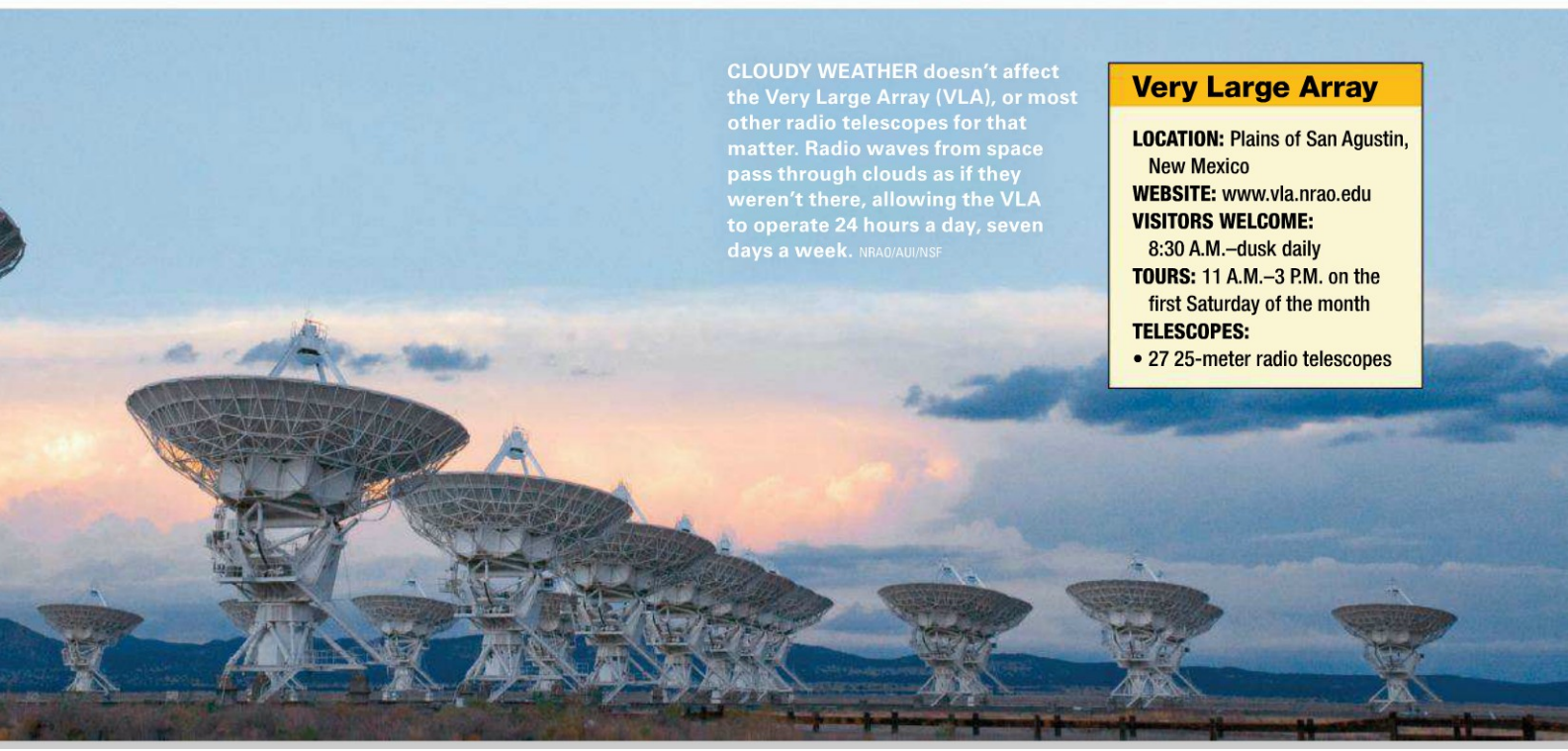
VISITORS WELCOME:

8:30 A.M.—dusk daily

TOURS: 11 A.M.—3 P.M. on the first Saturday of the month

TELESCOPES:

- 27 25-meter radio telescopes



ALMA Observatory

LOCATION: Atacama Desert, Chile**WEBSITE:** www.almaobservatory.org**VISITORS WELCOME & TOURS:** Possibly by first half of 2013 once construction finishes**TELESCOPES:**

- 50 12-meter short-wavelength radio telescopes
- 12 7-meter short-wavelength radio telescopes

ALMA

Atacama Desert, Chile

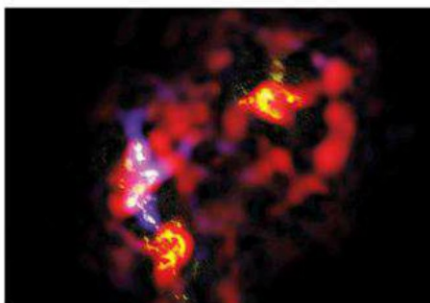
In the Atacama Desert of northern Chile, flocks of flamingoes promenade along brilliant salt lakes while donkeys graze among the scattered alfalfa. Llamas stroll the roadside south of San Pedro, the ancient birthplace of Chilean agriculture and now the modern hub of ecotourism in the country.

A wide, flat road climbs eastward into the martian-like landscape of eroded fault lines, dry riverbeds, and windswept dunes. Against mesmeric dark blue skies loom the cones of extinct volcanoes, a few draped with natural masterpieces made by the golden hues of sulfur.

The dusty road finally crests a ridge, and suddenly spanning this otherworldly plain is a geometric display of bright armored radio telescopes, all staring at the firmament.

This is the Chajnantor Plateau in northern Chile, the 16,500-foot (5,000 meters) elevation home of the world's most complex ground-based observatory, the Atacama Large Millimeter/submillimeter Array (ALMA). This facility combines the dreams of the National Radio Astronomy Observatory and its partners in Europe, East Asia, and the Republic of Chile.

By 2013, ALMA will be a reconfigurable array of 66 short-wavelength radio telescopes with two dish sizes. The twelve 7-meter telescopes sit in tight formation, flanked



THE ANTENNAE GALAXIES (NGC 4038 and NGC 4039) are colliding spirals. Early ALMA observations revealed star-forming clouds of cold, dense gas. ALMA (ESO/NAOJ/NRAO)

by four 12-meter telescopes, giving ALMA a constant high-sensitivity heart — the Atacama Compact Array. In addition, 50 more 12-meter telescopes in the main array can be moved, using the 28-wheeled ALMA transporters, to any of 192 pads across Chajnantor Plateau.

Behind the Cassegrain focus of each telescope hangs a cryogenically cooled thermos and receivers sensitive between 84 and 720 gigahertz. At its greatest span of 10 miles (16 kilometers), ALMA's resolution is an unrivaled 0.005 arcsecond using its highest frequency.

With only half the atmosphere present at sea level, extreme ultraviolet levels, and wind chills usually below freezing, workers and telescopes alike must be well protected. Each of the weather-clad telescopes is linked by underground fiber optics to the 17 PetaOp-speed ALMA Correlator supercomputer and its precision timing oscillators, protected inside a pressurized and climate-controlled space station-like facility.

Down at a more humane elevation of 9,500 feet (2,900m), the ALMA Operations Support Facility hosts hundreds of multinational staff. Here, the partners' telescopes are assembled and delivered to ALMA's high-tech telescope boot camp.

Round-the-clock shifts of radio astronomers and engineers test, tweak, and graduate each ALMA telescope. Whenever they slew the growing array across the sky, these folks are the first to see ALMA's early wonders, such as the previously unresolved star-forming regions in the colliding Antennae Galaxies.

Tip: Watch the ALMA construction at www.almaobservatory.org/en/live-from-the-alma-site/live-from-chajnantor.

**50
TIMES**
How much drier the
Atacama Desert
is vs. Death
Valley, CA

Arecibo

Arecibo, Puerto Rico

3 BY 6

Approximate size, in feet,
of each panel in
Arecibo dish

The Spanish colonial town of Arecibo rests on an enormous karst formation — soft stone pitted by millions of years of erosion. Throughout the surrounding Puerto Rican rainforest, enormous limestone caves and sinkholes abound, including the huge sinkhole that cradles the world's largest single-dish telescope, the Arecibo Observatory.

At 1,000 feet (305 meters) across, the spherical dish at Arecibo cannot move. A trampoline of strong steel cables supports its 38,778 aluminum panels, and, suspended above this surface, a traveling 900-ton platform carries the receivers.

Arecibo tunes to cosmic frequencies between 50 megahertz and 10 gigahertz using a Gregorian receiver unit and a long antenna line feed. Astronomers time their observations for when their target enters a virtual observing cone swept out 20° from the zenith (the overhead point). Both receiver units can slide out along a revolving track that moves either into the reflected waves.

Completed in 1963, the Arecibo Observatory is the world's most powerful radar transmitter. It studies Earth's ionosphere, and its location near the equator allows astronomers to probe all of the planets, moons, and asteroids in our solar system. The 20-acre collecting area of the big dish has helped astronomers discover the first exoplanets and map the cosmic distribution of galaxies. Arecibo is possibly best known for broadcasting humanity's first binary infographic message in 1974 in our search for extraterrestrial intelligences.

With some 54 inches (1.4m) of rain annually, temperatures in the upper 70s or low 80s, and a 500-step climb from the parking lot, visiting Arecibo is a sultry



Arecibo Observatory

LOCATION: Arecibo, Puerto Rico

WEBSITE: www.naic.edu

VISITORS WELCOME: 9 A.M.—4 P.M.

daily (closed Monday and Tuesday

January 16–May 31 and

August 1–December 14)

TELESCOPE:

• 305-meter Arecibo radio telescope

THE ARECIBO RADIO TELESCOPE collects low-energy cosmic radiation in a 20-acre dish that spans 1,000 feet (305 meters). In 1991, astronomers Aleksander Wolszczan and Dale Frail used this instrument to discover the first known exoplanets. NAIC/ARECIBO OBSERVATORY/NSF

adventure. Entrance fees are rewarded with a goggling view of the dish below. The Angel Ramos Foundation Visitor Center has hands-on astronomy exhibits, a gift shop, and a café. Tip: A good map or GPS will make the winding rainforest drive a lot more enjoyable.

No matter their size, shape, or frequency, these powerful marvels of

exploration eavesdrop exclusively on the universe's most private affairs, giving us our clearest insights into the cycles of the cosmos. Scientists and engineers push the boundaries of technology and endurance to build the biggest and best telescopes for this quest, a fact that is not lost on any visitor to these, America's greatest radio observatories. 📡

THE DESOLATE CHAJNANTOR PLAIN in the Chilean Andes lies 16,500 feet (5,000 meters) above sea level. The center of the Atacama Large Millimeter/submillimeter Array will lie near the center of this image (taken in 2010), not far from the distant building. ESO/F. KAMPHUES



HOW TECHNOLOGY is transforming astronomy

New innovation boosts telescope performance today and promises to revolutionize cosmic research in the years to come.

By Neville Woolf

"The prizes should be given to the telescopes," once said Joel Stebbins, longtime director of observatories in Illinois and Wisconsin. Those knowledgeable in horse racing recognize that a good horse is more important than a good jockey, but it isn't the same for astronomical discoveries — telescopes' operators, managers, designers, and mirror-makers tend to be forgotten.

Ground-based telescopes are becoming larger and making ever-more-distant and faint observations. As they do, the importance (and cost) of the facility, its operation, and management become just as crucial as the science concept that went into making the observations. Finally in

2010, the significance of this work was recognized when three developers of mirrors and telescopes — Roger Angel, Jerry Nelson, and Raymond Wilson — received the Kavli Prize in Astrophysics. This event reflects how important a detector's technology is for astronomical discoveries.

The practical side

It takes between 20 and 40 years to conceive, get funds for, design, and make a telescope, and it has remained that way for more than a century. A ground-based telescope stays a prime producer for about as long. (The time is usually much shorter in space, a few to 10 years, because most space scopes cannot be repaired.) Those who develop and plan a scope for use 30

to 60 years from now have to be in tune with future scientific goals and the options for future technology.

The quest to observe what has not been seen before, while minimizing cost, drives all new telescopes. The total instrument expense includes the many man-hours of the astronomers involved, as well as the instrument's construction and upkeep. Typically, the yearly cost of a telescope is around 10 percent of its construction cost. For a \$100-million telescope, the effective nightly cost would be nearly \$30,000.

If a group of smaller telescopes could make the same observation as a larger scope for a lower cost, then project leaders would go the less expensive route. The European Southern Observatory's (ESO)



THE GIANT MAGELLAN TELESCOPE at Las Campanas Observatory in Chile should begin operations in 2020. Scientists cast the second of the instrument's seven 8.4-meter mirrors at the University of Arizona's Steward Observatory Mirror Lab in January 2012. GIANT MAGELLAN TELESCOPE

Very Large Telescope (VLT), with its four 8.2-meter telescopes (see page 44), is one example. However, building a giant telescope is justified because of the tasks otherwise seen as impossible or impractical without it, such as seeing the faintest objects with enough detail to understand what they are, as well as their size, chemical makeup, and other characteristics.

Digging deeper

One learns more about a telescopic object by switching from imaging to spectroscopy, which analyzes light and reveals how matter absorbs and emits radiation. Increasing the detail captured allows scientists to determine what atomic elements are present and how hot they are. The least

time-consuming method is “least detail” spectroscopy, which is *just* adequate to distinguish between starlight and glowing gas. A least-detail spectroscopic observation will take about 100 times as long as a photographic image of the object. So, an observer using spectroscopy seeks the minimum amount of detail necessary to immediately identify the object type.

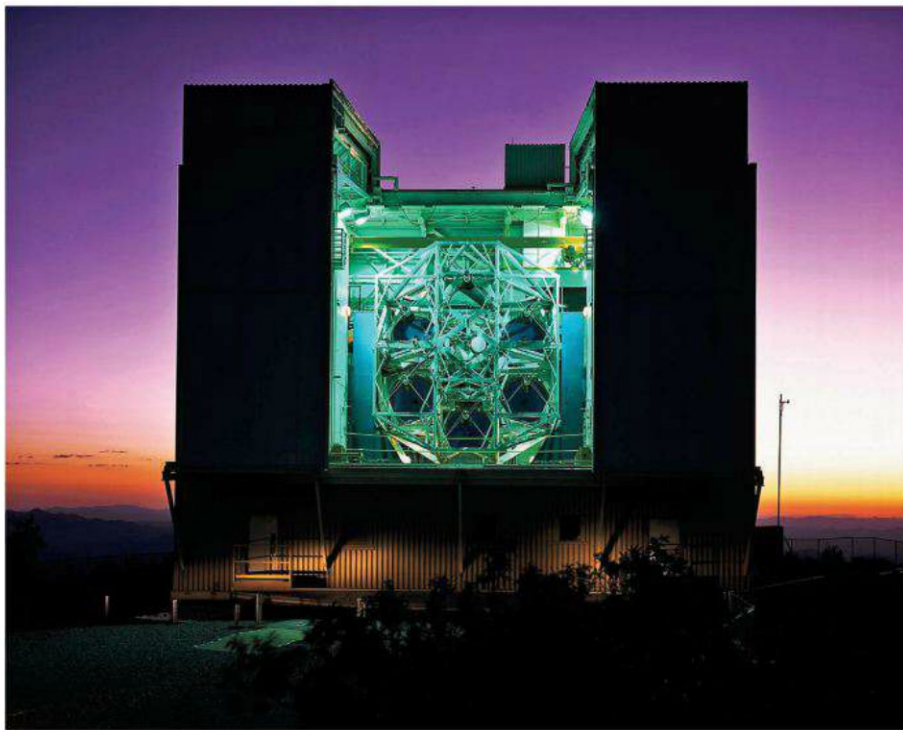
Astronomers use a giant telescope to observe extremely faint objects, where either the sky brightness or the electrical noise of the detector is limiting. (Sky brightness, or sky light, describes the night without moonlight. This is called “telescope dark time.”) In general, the sky brightness limits how faint an object can be for a photograph to capture it. For

spectroscopy, the detector usually sets the limit. Detectors and spectrographs have not yet reached their fundamental limits.

The ultimate limits of all telescopes (except radio) are set by the particle-like behavior of light. However, technology inefficiencies come from the way scientists put together their spectrographs, the detectors that are available, and the spurious counts that detectors generate. When we reach fundamental technical limits, observations will then be limited by how long astronomers are willing to spend targeting an object.

Telescope trade-offs

All telescopes and their surroundings (the structure and site) rely on a single



THE ORIGINAL MMT featured six mirrors, each only 1-inch thick. The quickness with which these mirrors reacted to temperature changes convinced University of Arizona astronomer Roger Angel that modern telescopes need to have thin, structured mirrors. MMT

analysis: The length of time to make a photographic observation of the faintest sources increases proportionally to the sky brightness at that specific wavelength. The telescope's mirror produces an image that is captured by pixels on a detector, like the chip in a digital camera. Light from the astronomical object illuminates each detector pixel, but this "wanted" light also mixes with sky light.

To make a spectroscopic measurement, astronomers use a metal sheet to keep out most of the unwanted light, and then a pinhole or slit lets through the light from the desired object. Unfortunately, this still lets through nearby sky light. The amount of sky brightness decreases as the image sharpens, and astronomers can use a smaller hole to isolate the object for spectroscopy or spread the image over more camera pixels to have less sky light mixed with the object to allow for better imaging.

A sharper image, of course, provides a huge benefit. The more blurred the image, the bigger the hole required to let

through its light. But a bigger hole lets in more unwanted sky light with the light astronomers want to measure. For a 0.5-arcsecond-wide image, the angular area of sky captured with the object is 16 times less than that of a 2-arcsecond-wide image. Observations of objects still fainter than that tiny patch of sky light would be 16 times faster relative to the larger image. But for a given telescope and image sharpness, and for objects fainter than the sky, it also takes 16 times as long to observe an object four times as faint. So each telescope has a practical limit to the faintest objects it can observe.

Doubling the diameter of a telescope's primary mirror halves the amount of time needed to capture an image of an object. A larger telescope produces a sharper image and has a fainter limit. To use a small telescope to observe an image that took six hours to observe with a larger telescope, the small scope needs days of observation, and then those spurious counts from the detector dominate, so the observation becomes impracticable anyway.

If astronomers study fuzzy objects — gas clouds or galaxies — there is no benefit to having a much sharper image than the object size, and scientists could make

such observations for less expense using a telescope with the same size mirror but less expensive optics that produce blurrier images. Numerous important observations of this kind, such as galaxy speeds, utilize these scopes.

Giant telescopes with moderate-quality images, such as the Hobby-Eberly Telescope (HET) at McDonald Observatory in Texas and the Southern African Large Telescope (SALT) near Sutherland, South Africa, can take advantage of such situations. Equally, telescopes designed to survey the entire sky and look for variable or moving objects, such as the Large Synoptic Survey Telescope (LSST) now under construction, also have to balance image size against field of view. LSST must choose between observing a huge area of sky and making the sharpest images. By current ordinary telescope standards, LSST will produce very sharp images. By comparison with the images that large telescopes can make for a small area of sky, however, LSST's images will be fuzzier.

Get rid of blur

Until the 1980s, astronomers thought Earth's atmosphere limited the image size of telescopes to 1 to 2 arcseconds, but since then they've learned that much of the blurring occurred in the domes and that the primary mirror of the telescope was often to blame. The reason is that a thick piece of glass holds heat. When the air near it is at a different temperature,



THE NEW TECHNOLOGY TELESCOPE at Chile's La Silla Observatory pioneered the use of active optics. The scope features a thin and flexible mirror 3.6 meters in diameter. The mirror keeps a perfect shape thanks to the pressure exerted by 75 actuators on its back. ESO/C. MADSEN

Neville Woolf, professor emeritus of astronomy at the University of Arizona, Tucson, has worked with telescope technology for decades.

3,200,000,000 The number of pixels that compose the Large Synoptic Survey Telescope's camera

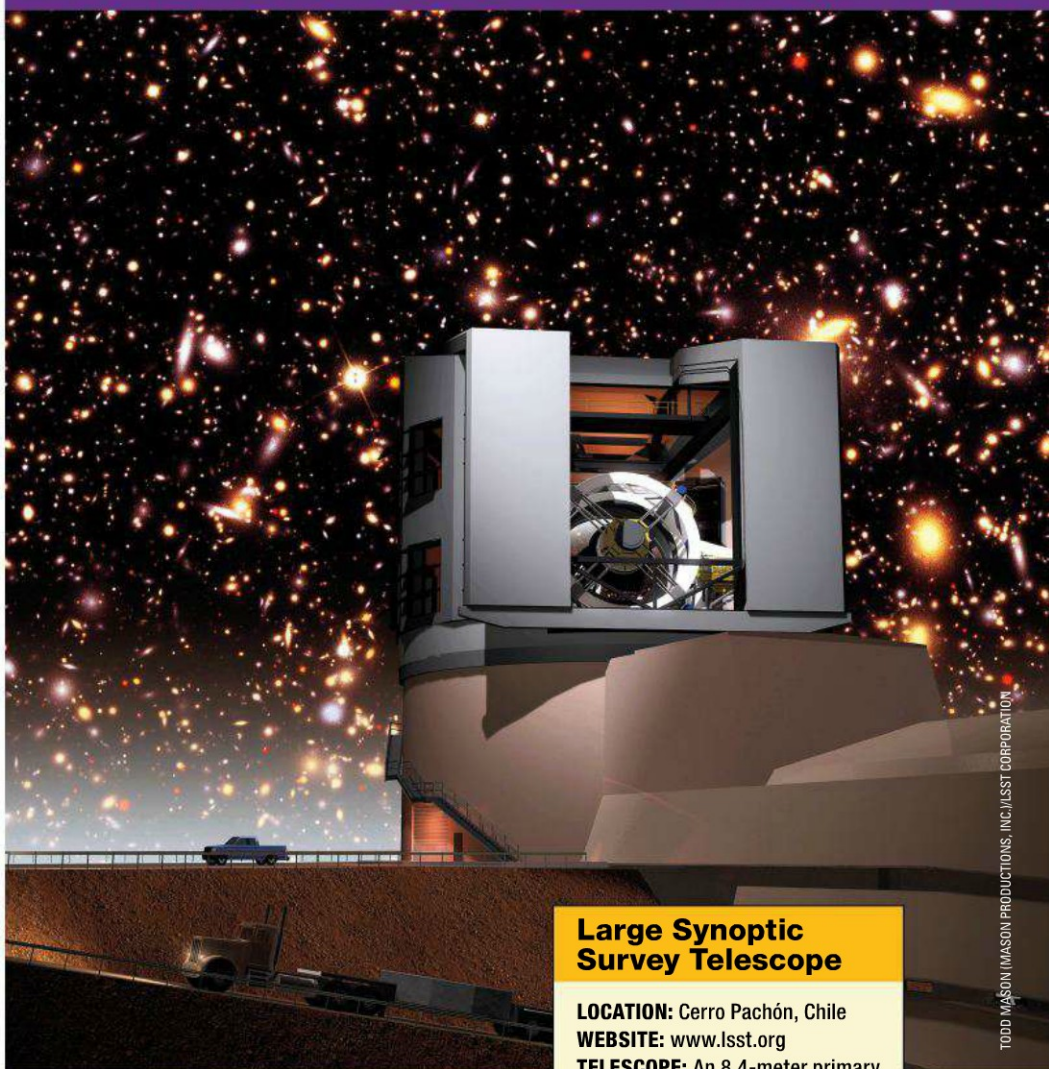
warm air currents carry the heat away, which spoils the image. A 1-inch-thick (2.5 centimeters) glass with heat escaping from one side takes more than an hour to halve its difference with air temperature. A 16-inch-thick (40.6cm) piece of glass takes many days to reach air temperature after a cold front has gone through. And the air layer near the mirror blurs the image by 0.5 arcsecond for each degree Celsius of temperature difference with the air. Mirrors need to be made of thin glass or used in a place with an extremely stable nighttime temperature (and kept at that same temperature during the day).

Engineers can loosen some of these restrictions by directing a smooth flow of nighttime air across the front surface of the mirror. This effectively isolates the primary from the bulk of the air above it. However, as the telescope mirror becomes bigger, such airflow is harder to manage, especially because any building that shelters the primary from wind gusts becomes too expensive.

The old six-mirror MMT atop Mount Hopkins, Arizona, used mirrors made with 1-inch-thick silica in an egg-crate structure. One night in the early 1980s, a cold front passed by Mount Hopkins as well as Kitt Peak (also in southeast Arizona), and telescope images at both locations appeared large and fuzzy. An hour later, the images at the MMT had shrunk considerably, but because all Kitt Peak telescopes of that era had thick mirrors, the images stayed bad that night and the next. This observation convinced University of Arizona astronomer Roger Angel that telescopes needed thin, structured mirrors.

Keep mirrors in check

Three issues are crucial when making large telescope mirrors. First, it takes more precision to support them as their size grows because, for a fixed-thickness mirror, the number of support points must increase at the same rate as the mirror area. Thin mirrors more than about 1 foot (30.5cm) wide need to be supported at many points, and the support may use observations of the image quality itself to make slow adjustments to tune the mirror shape. Raymond Wilson, then of ESO, discovered this solution when designing a 3.6-meter mirror for the New Technology Telescope at La Silla Observatory in Chile.



Large Synoptic Survey Telescope

LOCATION: Cerro Pachón, Chile

WEBSITE: www.lsst.org

TELESCOPE: An 8.4-meter primary mirror will survey the sky and cover 20,000 square degrees in about three days once operations begin late this decade.

THE LARGE SYNOPTIC SURVEY TELESCOPE will share the summit of Cerro Pachón with the Gemini South and the Southern Astrophysics Research scopes. Its 8.4-meter mirror will make it the mountain's largest.



WORKERS PREPARE to polish the Large Synoptic Survey Telescope's 8.4-meter primary and 5-meter tertiary mirrors, which were cast together at the University of Arizona's Steward Observatory Mirror Lab in December 2009. PAUL O'CONNOR/BNL/LSST



THE LARGE BINOCULAR TELESCOPE on Arizona's Mount Graham uses two borosilicate mirrors cast at the University of Arizona's Steward Observatory Mirror Lab. The MMT, LSST, and Magellan telescopes all use similar mirrors. JOHN HILL/LARGE BINOCULAR TELESCOPE CORPORATION

The second issue is that the mirror must not change its shape, especially from one part to another. So, if the mirror temperature differs across areas and the material experiences any appreciable expansion, it will warp out of shape — which is made correct to about 1 millionth of an inch for the best mirrors. Either the mirror must be made of extremely low-expansion material, or it must be maintained at a uniform internal temperature.

The third issue is that the mirror must be able to change its temperature at the same rate as night air. While this situation has vastly improved since the 1980s, telescopes are not yet reaching the limits set by outside hot or cold air currents. The most significant effects are in high-speed flows in the upper atmosphere and currents near the ground because there is so much structural material in a dome to be kept at air temperature.

Creating the mirrors

Those are the big issues that designers must pay attention to when planning large scopes, and there are three ways to make the mirrors to address those concerns.

Two variant telescope mirrors utilize hexagonal segments. Jerry Nelson developed one method, which is used at the two Keck telescopes on Mauna Kea in Hawaii and the 10.4-meter Gran Telescopio Canarias (GTC) on La Palma in the

Canary Islands, Spain. All these telescopes employ low-expansion glass 3 inches (7.6cm) thick and shaped as a paraboloid.

The second variant uses hexagons to make a spherical mirror, similar to the shape of the Arecibo radio telescope in Puerto Rico, but smaller. Both the HET and SALT employ 2-inch-thick (5.1cm) low-expansion glass, and they rotate in azimuth, which makes objects available for longer-duration observations. Because of the spherical primary, there must be a separate small secondary package to correct the telescope's "spherical aberration" for each star or galaxy observed.

Nelson's concept makes a paraboloid mirror in small segments or tiles, each stiff enough that a multiple-lever support can

passively hold them. Each individual mirror is a hexagonal segment about 60 inches (1.5m) in diameter. The segments are not physically connected to their neighbors, but sensors that cross the boundaries measure the vertical spacing of adjacent mirrors. This system keeps the segments connected to form a parabolic surface.

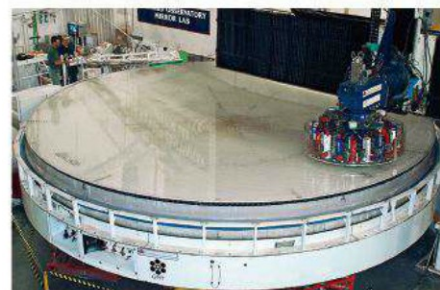
When Nelson developed his concept, the paraboloid sections were both hard to measure and polish. Circular mirror blanks are easier to polish than hexagons, so he used them and placed each segment in a warping harness when polishing the mirrors. When the harness was removed, the mirror would spring into the required off-axis shape. Unfortunately, when engineers cut the edges of each segment to form a hexagon, the stresses in the low-expansion material re-created distortion. When Nelson discovered this, he placed the warping harness back on and corrected the shapes to the original intent. Now all segments in his telescopes' primaries wear them. While this method simplifies mirror construction, it introduces difficulty when bringing the separate light together for each observed object.

Angel has produced borosilicate mirrors that allow internal cooling. The "new" 6.5-meter MMT; the two 6.5-meter Magellan telescopes at Las Campanas, Chile; and the two 8.4-meter mirrors of the Large Binocular Telescope (LBT) on Mount Graham, Arizona, use this technology. The LSST also will use an 8.4-meter Angel mirror.

Angel's concept took a different route: Make mirrors with glass no thicker than 1 inch, but with an internal structure able to withstand wind distortion in an open



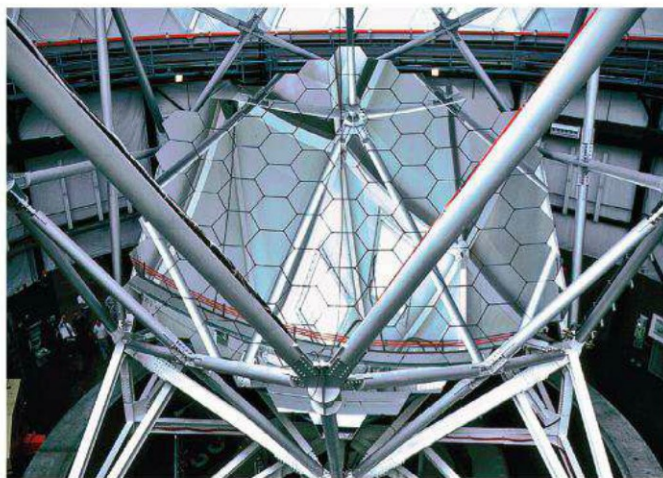
TECHNICIANS LOAD CHUNKS OF GLASS for the LSST's 8.4-meter primary into the furnace mold at the University of Arizona's Steward Observatory Mirror Lab. It took 51,900 pounds (23,540 kilograms) of glass to make this mirror. RAY BERTRAM/SOML



A POLISHING MACHINE at the University of Arizona's Steward Observatory Mirror Lab slowly smooths the surface of the first 8.4-meter mirror destined for the Giant Magellan Telescope in Chile. The lab cast this mirror in 2005. SOML/UA



THE 36 HEXAGONAL SEGMENTS of the Gran Telescopio Canarias' 10.4-meter parabolic mirror are made from 3-inch-thick glass. The Keck telescopes use a similar design. PABLO BONET AND THE IAC'S PHOTO ARCHIVE



THE HOBBY-EBERLY TELESCOPE, like the South African Large Telescope, uses 91 2-inch-thick hexagonal segments to create an effectively 9.2-meter spherical mirror. MARTY HARRIS/MCDONALD OBSERVATORY

telescope enclosure. About 80 percent of the mirror's volume is air space. Before melting the glass, engineers place shaped aluminum silicate cores into a mirror blank. Silicon carbide nuts and bolts hold down the cores and prevent them from floating in the molten glass. The glass is then electrically heated to its melting point in a special furnace, which rotates at a specific speed to create the desired parabolic shape on the surface.

After the glass has solidified and cooled, technicians use water jets to clean out the cores and remove the silicon carbide pieces. Technicians use machines to grind the surface and polish it to the required shape. To avoid the "Hubble trouble," where a mirror was polished to the wrong shape, engineers use two independent methods to test the surface curvature.

Angel's 8.4-meter mirrors have a focal ratio of $f/1.14$, which enables compact telescopes. The primary's shape differs from a sphere 40 times more than the mirror of the 200-inch Hale Telescope atop Palomar Mountain does, a measure of the difficulty of polishing by conventional methods.

Up the mountain

After a primary mirror is made, engineers must bring it to the observatory site — and this can also be a challenge. While Nelson mirrors are small pieces and therefore easy to move, the largest mirrors currently brought to sites are more than 8.2 meters in diameter — that's nearly 27 feet. Technicians place the mirror into a steel case and then load it on a

flatbed for freeway transportation. If instead it needs to be shipped, at the port they weld the steel case to the ship deck because it is too large to go in a hatch. Then, at the arrival port it is unwelded and put back on the flatbed.

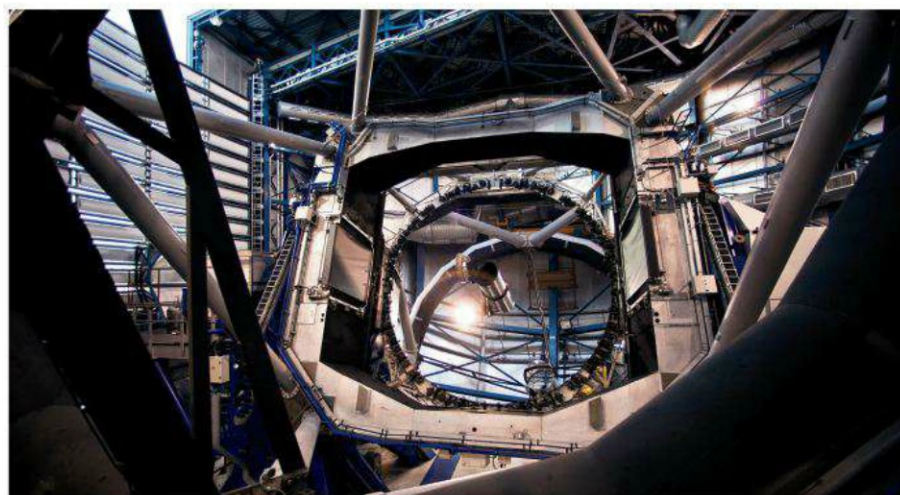
On the mountain road near its destination, the mirror is nearly upright because of the limited road width. Mountain roads have inslopes and outslopes, so the flatbed has a large weight that moves from side to side to keep the center of mass positioned between the wheels.

Optics that adapt

Large mirrors gather more light, but it is also important to create sharp images. This is where adaptive optics comes in.

Sharper images are necessary when telescopes capture crowded images, especially when observing individual faint stars in galaxies or planets orbiting stars other than the Sun. (It is not surprising that these are "hot" areas of astronomy today because they require the largest possible telescopes and also call on the most-advanced technology.)

Wilson first introduced *active* optics. This technique monitors the image that the scope produces and actively bends the primary mirror to correct the blurring caused by gravitational distortion of the mirror's shape and similar misalignment of the primary and secondary mirrors. Most telescopes with single giant mirrors use this technology, such as the VLT's



EACH OF THE 8.2-METER UNIT TELESCOPES of the Very Large Telescope at Chile's Paranal Observatory uses active optics to correct for atmospheric effects by bending a thin, flexible primary mirror. The Gemini and Subaru telescopes use a similar technique. ESO



THE LONG AND WINDING ROAD up Arizona's Mount Graham had a wide load **October 21, 2003** — the Large Binocular Telescope's first 8.4-meter mirror. Transporting monolithic mirrors to mountaintops is a hazard of modern telescope construction. JOHN HILL AND JIM SLAGLE/LBTC

four 8.2-meter telescopes in Paranal, Chile; the 8.1-meter Gemini telescopes on Mauna Kea, Hawaii, and at Cerro Pachón, Chile; and the 8.2-meter Subaru Telescope on Mauna Kea.

Active optics improves image sharpness, but it is inadequate to correct for the rapid flickering and distortion of the image as air currents traverse the light path above the telescope. This requires *adaptive* optics, which is also convenient for spectroscopy because the size of a spectrograph for an image produced by adaptive optics is relatively small and independent of the telescope's size.

Adaptive optics can sharpen images to as small as the diffraction limit of a telescope. This limit comes about because radiation travels as waves. The visible-wavelength image of a bright star in a 4-inch scope is a spot about 1 arcsecond across its brightest part and a series of faint rings around it. If Earth's atmosphere were perfectly still, then an 8-inch telescope would make images 0.5 arcsecond across, and a 400-inch (10m) telescope would make star images 0.01 arcsecond across. But instead, because of air currents, the image of a very bright star in a large telescope is a series of rapidly moving points of light called "speckles." Each one is the size of the telescope's diffraction spot, but they are fainter and crowded together to make a fuzzy image, whose

size is determined by the "seeing" — a measure of the atmospheric quality.

To stack the speckles atop one another (which helps create a more-precise observation) and to make the light wave peaks arrive together, the telescope needs to collect the incoming light on a flexible mirror whose shape can be altered every $\frac{1}{1,000}$ second to exactly compensate for the changing atmosphere. This adaptive optics technology allows a small field of view in which the images can be diffraction limited, often just a few arcseconds across, because the atmosphere in the line of sight changes from star to star. At longer wavelengths, the diffraction spot and the sky area with a well-corrected image increase.

When observing galaxies and quasars, there usually isn't a star bright enough in the field of view to determine the needed corrections, so astronomers use artificial stars. Lasers attached to the telescope create these "stars" by each illuminating

a spot in the upper atmosphere. Large telescopes host a number of laser stars because the expanding cone of returning laser light that ends in the primary mirror passes through a region of the upper atmosphere that is smaller than the telescope mirror. Additional laser spots on the sky around the object correct for the atmospheric disturbances here. And to avoid confusing the data, science observations use a filter that rejects laser light. Because telescopes are not yet large enough to discover the limits of adaptive optics, we do not yet know where, or if, the value of this technology will bottom out.

The expense of observing increasingly fainter objects is extremely high, and a telescope's cost increases faster than its mirror area. To observe objects twice as faint as the limit of a smaller telescope, scientists must request an instrument that costs about six times as much. Very large telescopes can only be justified if their makers have done everything possible to make their images sharper.

What needs adapting

Observations of planetary systems, very distant stars, or galaxies at near-infrared wavelengths employ adaptive optics differently. For planetary systems, the main goal is to get rid of as much of the central star's scattered light as possible and to see the planets. Superb images are necessary, with different correction at different wavelengths, and with phase filters to move the light of diffraction rings all to one side of the image. Astronomers make two observations, first with the excess light on one side, and then on the other.

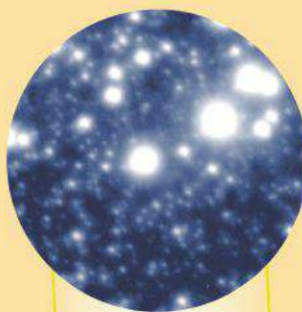
Although astronomers have made the first pictures of extrasolar systems, the goal of observing a number of planetary systems with their terrestrial planets is still far away. Scientists estimate that a ground-based telescope capable of making such observations needs to be at least 100 meters wide.



DIFFRACTION OF LIGHT limits the ability to see fine details in images. Even a star appears as a disk surrounded by fading concentric rings. The disk becomes smaller with increasing aperture (left to right, three left panels) but never disappears. Adjacent stars thus blend together (right). This is the main reason astronomers desire big scopes. ASTRONOMY: ROEN KELLY

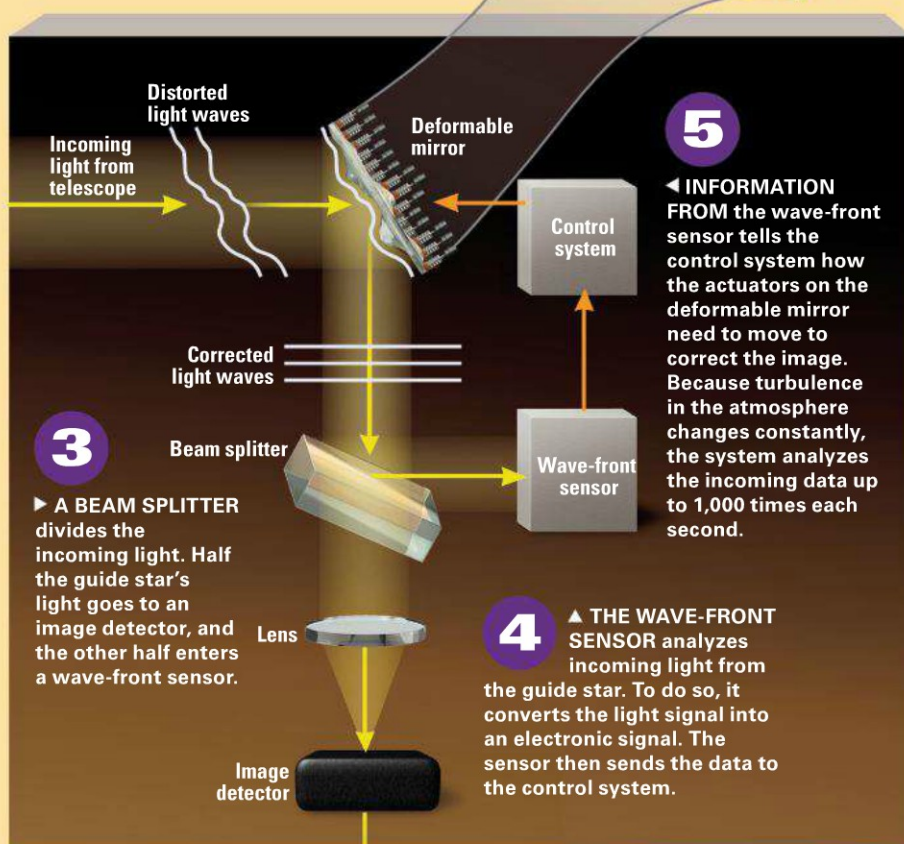
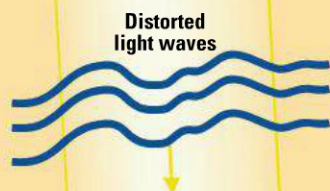
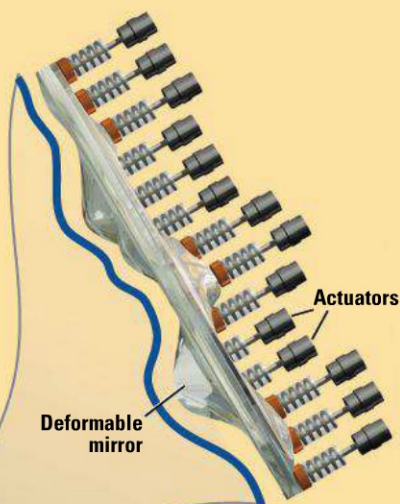
How adaptive optics works

The deformable mirror and all the electronics associated with adaptive optics are in one instrument. Incoming light first reflects off the telescope's primary, secondary, and tertiary mirrors before it enters the adaptive optics system, which is housed at one of the telescope's focal points. The system's deformable mirror is a few centimeters in diameter and a few millimeters thick. ASTRONOMY: ROEN KELLY

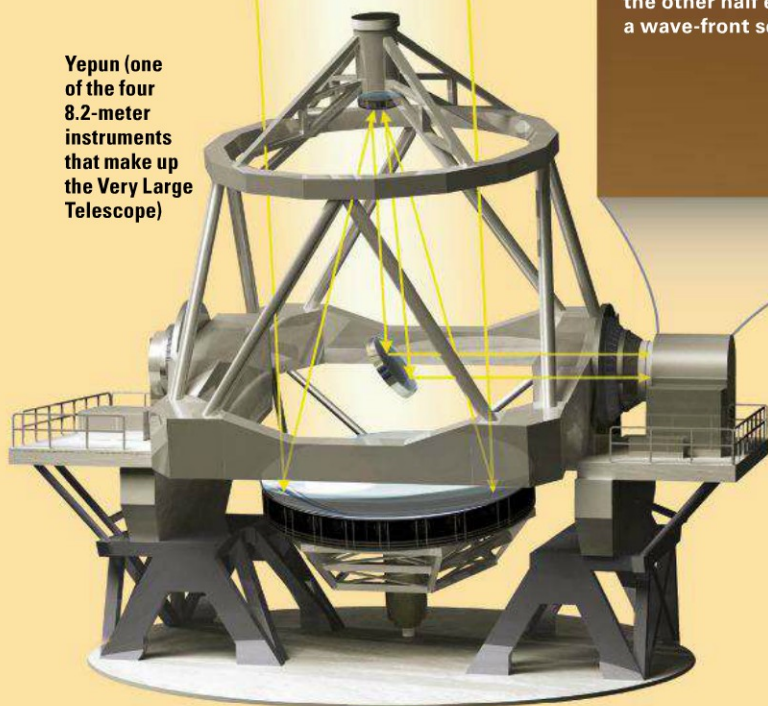


1 **◀ LIGHT FROM DISTANT STARS** appears smeared and distorted to ground-based telescopes due to turbulence in Earth's atmosphere. GEMINI OBSERVATORY

2 **▶ ACTUATORS THAT CONTROL** the mirror's shape sit on the back of the deformable mirror. When the wave-front sensor detects turbulence, a change in voltage causes an actuator to expand or contract, similar to a piston in a car's engine. This example shows a single flexible mirror, but some telescopes use segmented adaptive mirrors. Future adaptive optics systems will use larger mirrors with thousands of actuators.



Yepun (one of the four 8.2-meter instruments that make up the Very Large Telescope)



6 **◀ THE CAPTURED IMAGE OF STARS** is much sharper after the light passes through the adaptive optics system. This technology helps factor out the distortion effects from Earth's atmosphere. GEMINI OBSERVATORY



A LASER BEAM shoots toward the Milky Way's center from Yepun, one of the four instruments that constitute the Very Large Telescope in Chile. The beam creates an artificial star that allows the scope's adaptive optics system to eliminate atmospheric blurring. ESO/YURI BELETSKY

Most of the time, a fair portion of the blurring occurs in the telescope (due to misalignment or a bad focus of the optics) and in the atmosphere's lower layers, and it is possible to correct for them. "Ground-layer correction" has a moderately large field of view, typically a few arcminutes, compared to just a few arcseconds of normal adaptive optics. This technique coupled to multiple-object spectroscopy may become the standard method of observing many compact objects, stars, quasars, or

distant galaxies at a time because the reduced sky light entering with each image permits fainter objects to be visible. The "faintness limit" for the telescope will improve by a factor of four to 10 compared to ordinary multiple-object spectroscopy.

Multiple spaced-out "smaller" telescopes such as the VLT can also benefit from ground-layer correction technology. The universe's expansion increases the wavelength at which the first stars and quasars need to be observed by about a

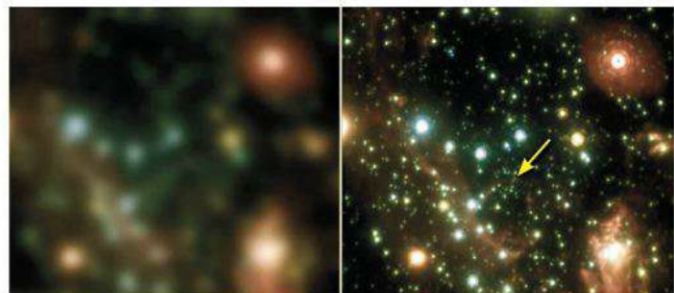
factor of eight. And so, the light from these objects falls in the infrared, for which adaptive optics works well.

Space versus ground

Space telescopes can also make sharp images, and they work with a much darker "sky." The James Webb Space Telescope (JWST), which is expected to cost about \$8 billion by the time it launches in 2018, seems near the affordable limit for space telescopes, but it has the risks of a



THREE LASERS joust above Hawaii's Mauna Kea as Subaru (left) and the twin Keck telescopes use their adaptive optics systems. Keck II's beam appears thickest. ANDREW COOPER (W. M. KECK OBSERVATORY)



ADAPTIVE OPTICS (AO) turns blurry scenes into tack-sharp images. Astronomers took both of these photos of the Milky Way Galaxy's central region through one of the 10-meter Keck telescopes — the one at left is without AO and the one at right with. The AO image resolves dozens of individual stars and even pinpoints the location of Sagittarius A* (arrow), the supermassive black hole that marks the galaxy's center. KECK OBSERVATORY/UCLA GALACTIC CENTER GROUP

15 The diameter of the Thirty Meter Telescope's field of view, in arcminutes — that's half the size of the Moon.

single launch and an unrepairable telescope. If its 6.5-meter mirror works perfectly, JWST will produce diffraction-limited images. So, essentially it will achieve the best we can in space, unless in the future we can find a way to send up a larger mirror for the same expense.

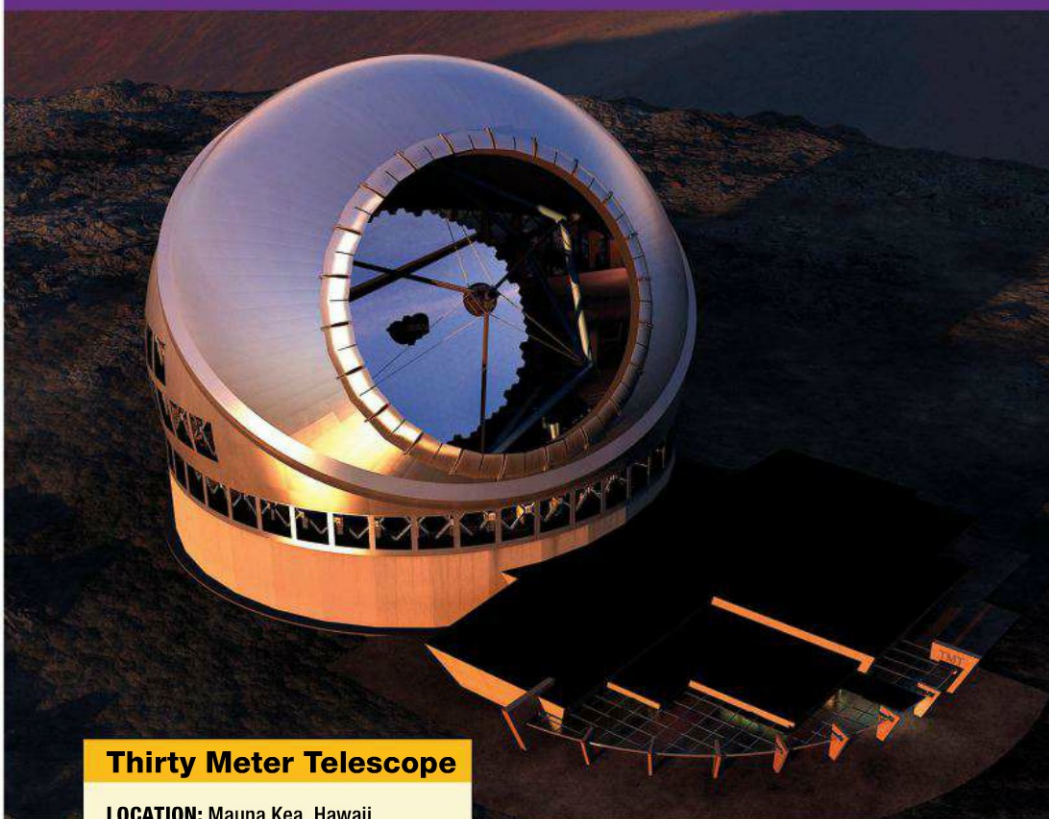
If we assume that the future Giant Magellan Telescope (GMT), a 24.5-meter equivalent-area instrument, can also produce diffraction-limited images, then it will be similar to JWST in its image faintness limit at the 1–2.5 micron range in the near infrared. The GMT will be inferior at longer wavelengths where the telescope's heat emission and atmosphere dominate, but it will be better at shorter wavelengths if — and it is a big if — the adaptive optics system can make diffraction-limited images. Unless the seeing is extremely good, adaptive mirrors unfortunately cannot keep up with precise correction for the changing atmosphere when observing at visible and red wavelengths. JWST will be more sensitive at longer infrared wavelengths, but ground observations will show more detail for angular structure. Spectroscopic observations at wavelengths shorter than 2 microns in general will be more sensitive from the ground.

Astronomers have shown that “multi-conjugate adaptive optics” (MCAO) also works well. In this technique, not only are the ground-layer effects separately corrected, but additional atmospheric layer zones are, too. MCAO improves upon the limited field of view of classical single adaptive mirrors, and it can produce sharp images over an arcminute instead of just arcseconds, although this isn't as wide an area as ground-layer correction alone. It is the adaptive optics of the more-distant future.

What tomorrow holds

One of the main issues when developing ultra-large telescopes is determining which type of mirror will be best. Both Angel's and Nelson's mirrors have had designs produced around them.

The GMT's primary mirror is a close-spaced group of seven Angel 8.4-meter mirrors forming a paraboloid surface centered on the middle mirror. The challenge in this design is that the surface of the outer six mirror segments is not radially symmetrical — the optical axis doesn't line up with the aperture's mechanical



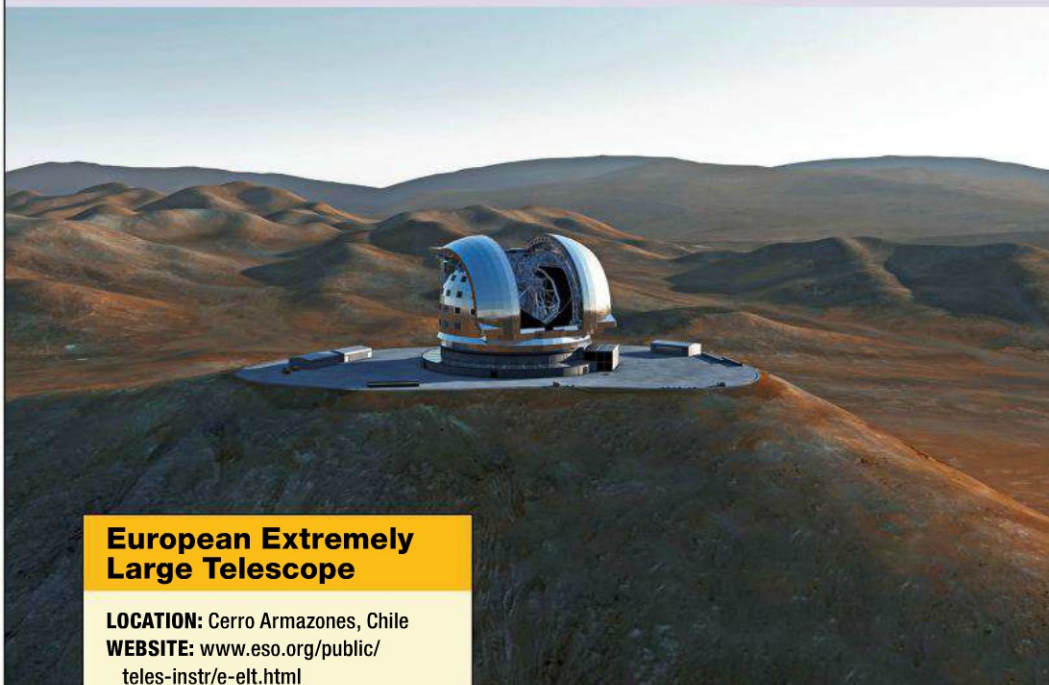
Thirty Meter Telescope

LOCATION: Mauna Kea, Hawaii

WEBSITE: www.tmt.org

TELESCOPE: The 30-meter primary mirror will be composed of 492 hexagonal segments 1.44 meters across.

THE THIRTY METER TELESCOPE will collect nearly 10 times the light of each of its Keck neighbors. Researchers hope the behemoth will be taking data by this decade's end. TMT OBSERVATORY CORPORATION



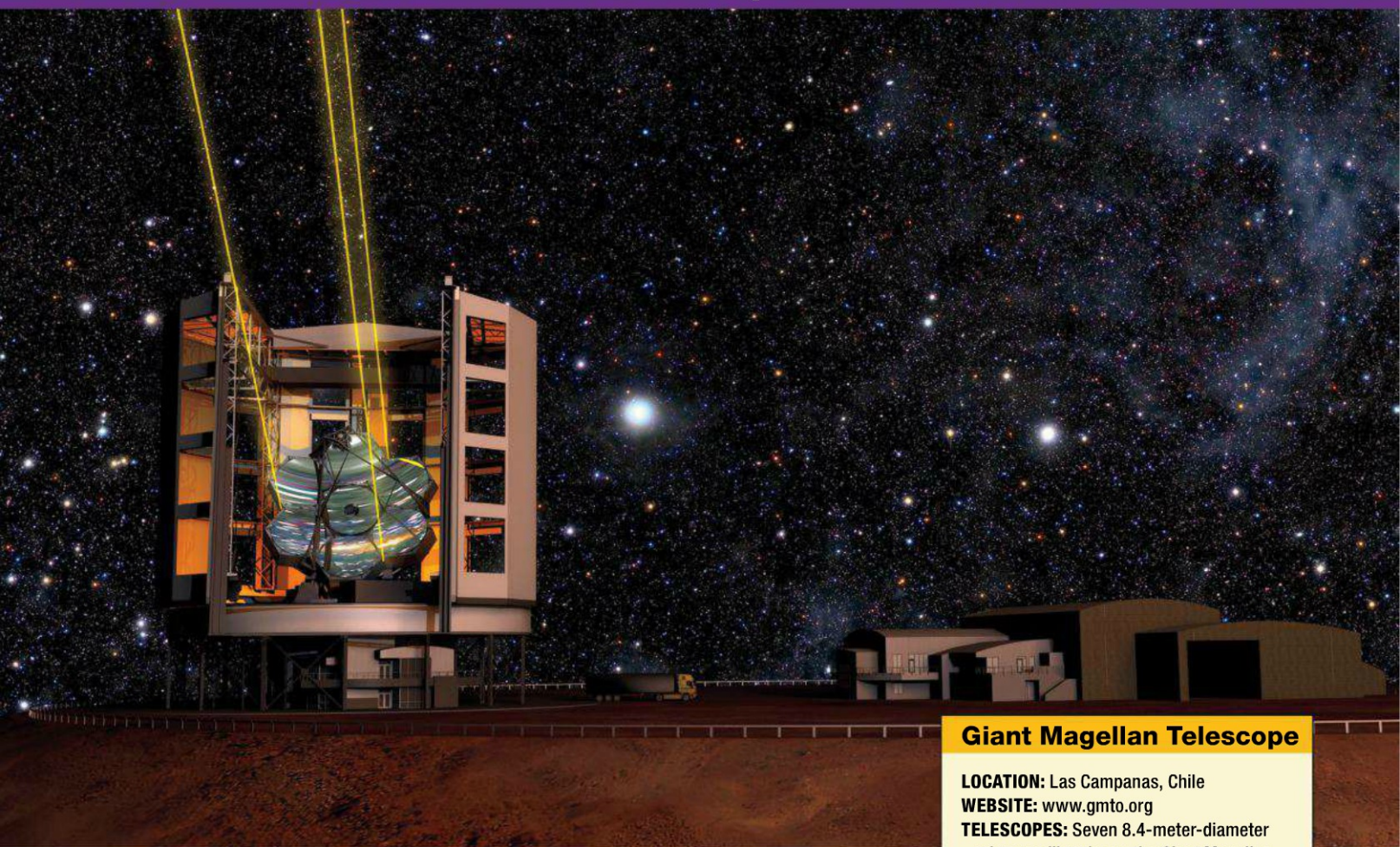
European Extremely Large Telescope

LOCATION: Cerro Armazones, Chile

WEBSITE: www.eso.org/public/teles-instr/e-elt.html

TELESCOPES: This 39.3-meter aperture telescope, scheduled for first light in the early 2020s, incorporates about 1,000 hexagonal segments.

THE LARGEST TELESCOPE in the world a decade from now may well be the 39.3-meter European Extremely Large Telescope. It will view the cosmos from Chile's Cerro Armazones. ESO



THE GIANT MAGELLAN TELESCOPE is well on its way from concept to completion. The University of Arizona's Steward Observatory Mirror Lab has cast two of the scope's seven 8.4-meter mirrors and nearly finished polishing the first. Construction workers expect to break ground for the project at Las Campanas Observatory in Chile this year. The instrument will use adaptive optics and other recent breakthrough technologies. GIANT MAGELLAN TELESCOPE

Giant Magellan Telescope

LOCATION: Las Campanas, Chile

WEBSITE: www.gmto.org

TELESCOPES: Seven 8.4-meter-diameter mirrors will make up the Giant Magellan Telescope. It will have the resolving power of a 24.5-meter telescope and the equivalent collecting area of a 21.4-meter scope.

center. This requires a modification of the usual polishing and measuring procedure. While the first of these mirrors was cast in 2005, the polishing is not yet completed. It is already diffraction limited at visible wavelengths, and the finishing work is improving the image quality. A second mirror was cast January 14, 2012.

The GMT's circular mirrors cannot fill a continuous circular space; however, the scope's secondary mirror also consists of seven pieces, each matched to one of the seven primary segments. This means the phasing of the mirrors can be handled adaptively by adjusting the vertical placing of these seven.

The future segmented Thirty Meter Telescope (TMT) will contain 492 hexagonal mirrors. The adaptive secondary

mirror cannot match the hexagons of the primary mirror (with current technology), so the hexagons will have to move to properly phase the observations. Scientists don't yet know if the GMT or the TMT's technology will work better. The 39.3-meter European Extremely Large Telescope is also on the drawing board, and construction is expected to begin this year.

A third type of extremely large telescope is also possible. This is essentially an extension of the LBT concept and would use a large number of 8-meter mirrors with the images brought together as a single phased image. An advantage of such a technology is that the individual mirrors could be separately used for ground-layer adaptive work with mass-produced spectrographs.

Extending the universe

The distant universe beckoned the designers of the 200-inch Hale Telescope in the 1920s. And after scientists built it, the work paid off. The instrument showed quasars, explored galaxies in different stages of development, gave hints that the universe's expansion is accelerating, and furthered our understanding of the origin of chemical elements.

The largest current and future telescopes will push that research further and also study the nearby universe — the world of planetary systems that beckon today's telescope designers. At no time has it been clear what the new horizon offered, but those possibilities justify the cost of the coming generation of extremely large telescopes. ●

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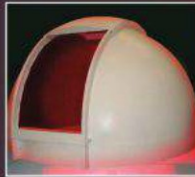
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